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ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

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AGARD REPORT No. 661

Factors of Safety

Historical Development, State of the Art and Future Outlook

NORTH ATLANTIC TREATY ORGANIZATION

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ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD

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(NORTH ATLANTIC TREATY ORGANIZATION)

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PREFACE

The concept of the factors of structural safety presently applied to the design of fixed-wing aircraft can be traced back some 50 years. The numerical values of these factors are based on experience hidden away in history, and literature and requirements only give indications of the various aspects which the factors are intended to cover, thus showing a lack of rational definition.

The last decades have brought about rapid progress in establishing aerodynamic derivatives, defining load conditions and predicting structural loads as well as enabling more detailed analyses for stress and deformation to be made.

The lack of a rational basis for the factors of safety together with the progress made brought about a discussion of changing the concept and the factors involved. AGARD Structural and Materials Panel formed an ad hoc Group to condense this discussion.

The three pilot papers contained in this report address the different aspects which are envisaged, and show up inconsistencies of the present concept as well as means and methods for possible changes and examples of the outcome. An additional paper summarizes what is going on in the field of civil engineering with respect to structural safety.

It is hoped that these papers will rise to a concerted effort towards rationalizing the concept of structural safety in aircraft design.

R.J.MEYER-JENS
Chairman, Ad Hoc Group
on Factors of Safety

CONTENTS

FACTOR OF SAFETY/LIMIT LOAD CONCEPT-MAXIMUM LOAD CONCEPT

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SUMMARY

It is the philosophy of the present airworthiness regulations for airplane design to define the expected loads during operation in terms of limit loads. The required margin of safety between these limit loads and the ultimate loads has until now been covered by a factor of safety of 1.5. The proposal is made to rethink the philosophy of having a fixed factor of safety, taking into account the probability of load occurrences and variations in the properties of materials. The load level of limited loads or of extremely rare occurrences could then be defined as maximum loads with a lower factor of safety. Three possible methods of predicting maximum loads are proposed.

1.0 INTRODUCTION

The present-day safety factor for aircraft structures, as applied to manned aircraft, dates back 50 years. During this period considerable progress has been made, expecially in the fields of structural materials, semifinished products, and testing methods. Furthermore advances in aerodynamics and aeroelasticity, combined with developments in electronic data processing (EDP), facilitate a better prediction of structural loads.

A reappraisal of the safety factor would therefore seem to be in order, not with the intention of lowering the level of safety, but with the aim of examining the various safety requirements in the light of present knowledge. In this connection design loads should be defined as those loads that will be exceeded only with a small probability. They are then called maximum loads. At present possibilities for the application of this view are visualized mainly for military aircraft, and three possible methods are recommended:

- semi-statistical/semi-deterministic
- statistical: Extreme-value distribution
- semi-statistical/semi-empirical

2.0 LIMIT LOAD CONCEPT

2.1 Historical Review

Since the early days of aviation all countries engaged in aircraft constrution have been concerned with safety in aircraft design. Safety factors were introduced into the design of the structure to take care of uncertainties which could not be properly assessed by the technological means of that time, such as

a) the possible occurrence of load levels higher than the limit load

b) uncertainties in the theoretical or experimental determination of stresses

c) scatter in the properties of structural materials, and inaccuracies in workmanship and production

c) deterioration of the strenght of materials during the operational life of the aircraft

Figure 1 shows the development of the safety factor as required by American, British, French, and earlier German regulations. In comparing American and German regulations it should be kept in mind that limit loads were defined differently, so that the American specification CAR yields higher ultimate loads, although the corresponding safety factor is smaller, e.g., since

$n_u = j \times n_1$ for large gross weights

$n_u = 1.5 \times 2.5 = 3.75$ for CAR

$n_u = 1.8 \times 2.0 = 3.60$ for BVF

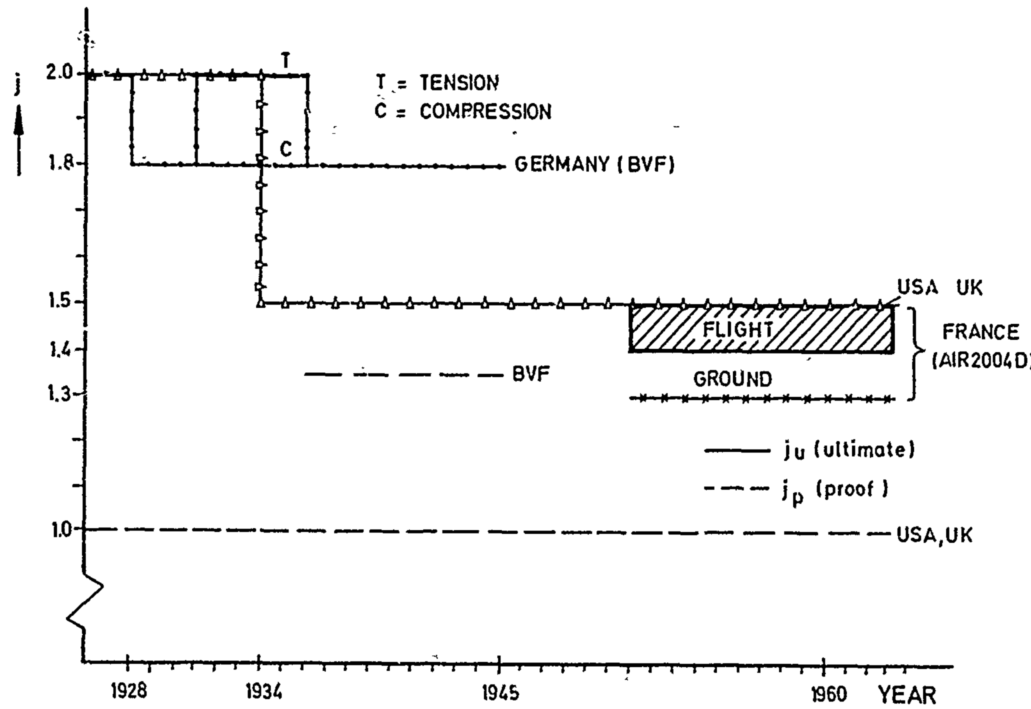

FIG.1 HISTORY OF SAFETY FACTORS

	j_u	j_p	j_u / j_p
FRANCE AIR 2004D FLIGHT GROUND	 1.4 ÷ 1.5 1.3	 — —	 — —
UK Av.P·970 BCAR	1.33 ÷ 1.5 1.5	1.0 ÷ 1.125 1.0	1.5 ÷ 1.18 1.5
USA MIL FAR	1.5	1.0	1.5
GERMANY BVF until 1945	1.8	1.35	1.33

TABLE 1 SAFETY FACTORS OF SEVERAL REGULATIONS

The corresponding values for the yield safety factor, or factor of proof test, j_p, for the various countries is also shown in Table 1. The ratio j_u/j_p is given as about 1.5 by currently valid American and British specifications, with the exception of the British military specification Av.P. 970. It distinguishes two groups (Reference 6)

a) cases for which the load level is not limited by the capabilities of the aircraft but is defined on the basis of experience, with safety factors as listed in Table 1

b) cases where the aircraft is incapable of producing operational loads in excess of prescribed load levels, or where operational loads are limited by reliable means. For these cases an ultimate factor j_u is not defined.

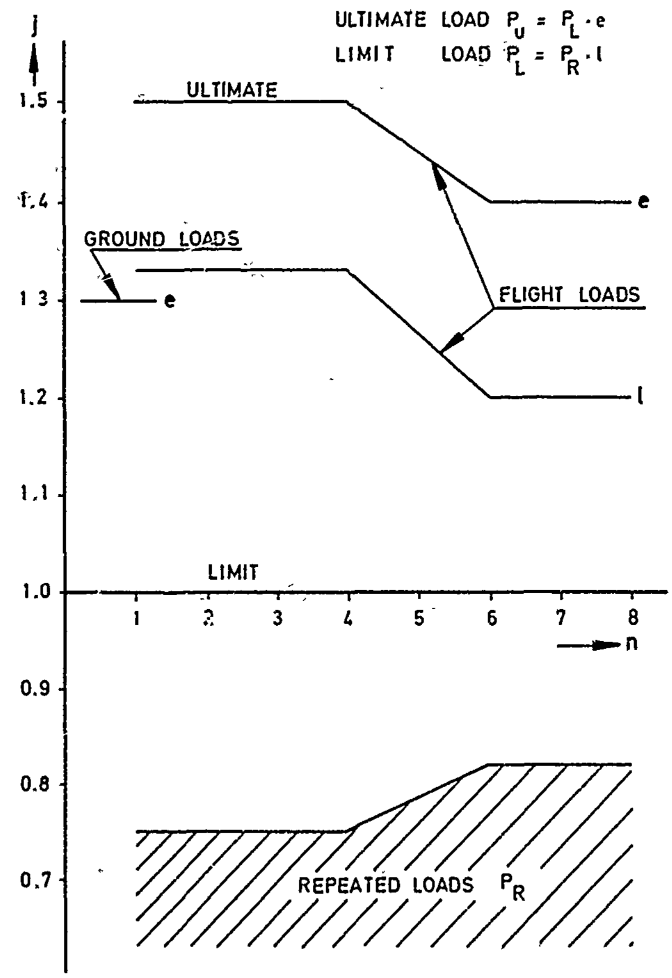

FIG. 2 SAFETY FACTORS - AIR 2004 D

The French military specifications AIR 2004/D (Reference 4) require various ultimate factors. For ground loads the factor j_u decreases to 1.3 for the undercarriage and its support structure. For flight loads the ultimate factor depends on the category of aircraft, i.e. on the maneuver load factor. In addition to this the concept of frequent loads (charges sûres, or charges de base) has been introduced into the AIR 2004/D Regulation. They are defined as the maximum loads occurring during normal operation, and differ from limit loads by a factor of l. This factor depends also on the aircraft category. Fig. 2 shows the safety factors according to AIR 2004/D in relation to limit load. Beyond this limit, loads are required not to cause permanent deformations larger than 5 % of deformations under this load.

The ratio of ultimate stress to yield stress has decreased continuously with the increasing use of high-strength materials, so that currently its value ranges between 1.1 and 1.5. Fig. 3 shows the trend of the last four decades. It is interesting to note that the ultimate factor of safety was defined in 1934, when the aluminum alloy 2024 with approximately the same ratio of ultimate to yield strength had generally come into use in aircraft construction.

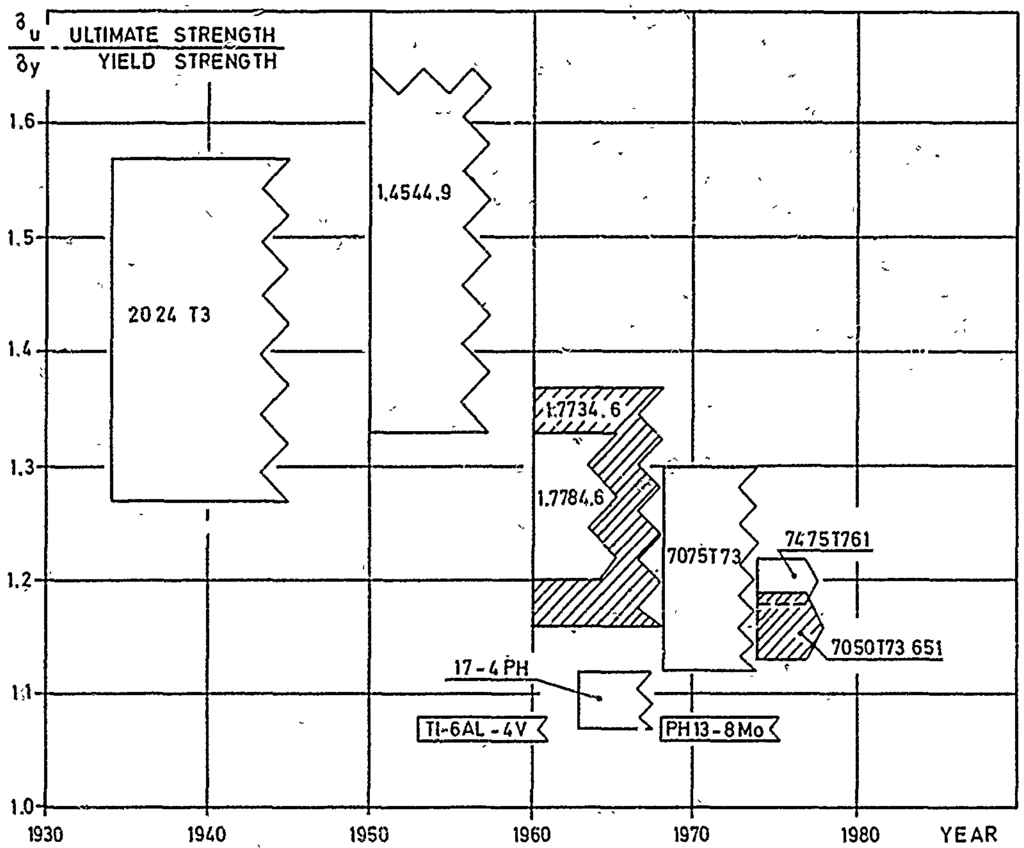

FIG. 3 TREND IN USE OF STRUCTURAL MATERIALS

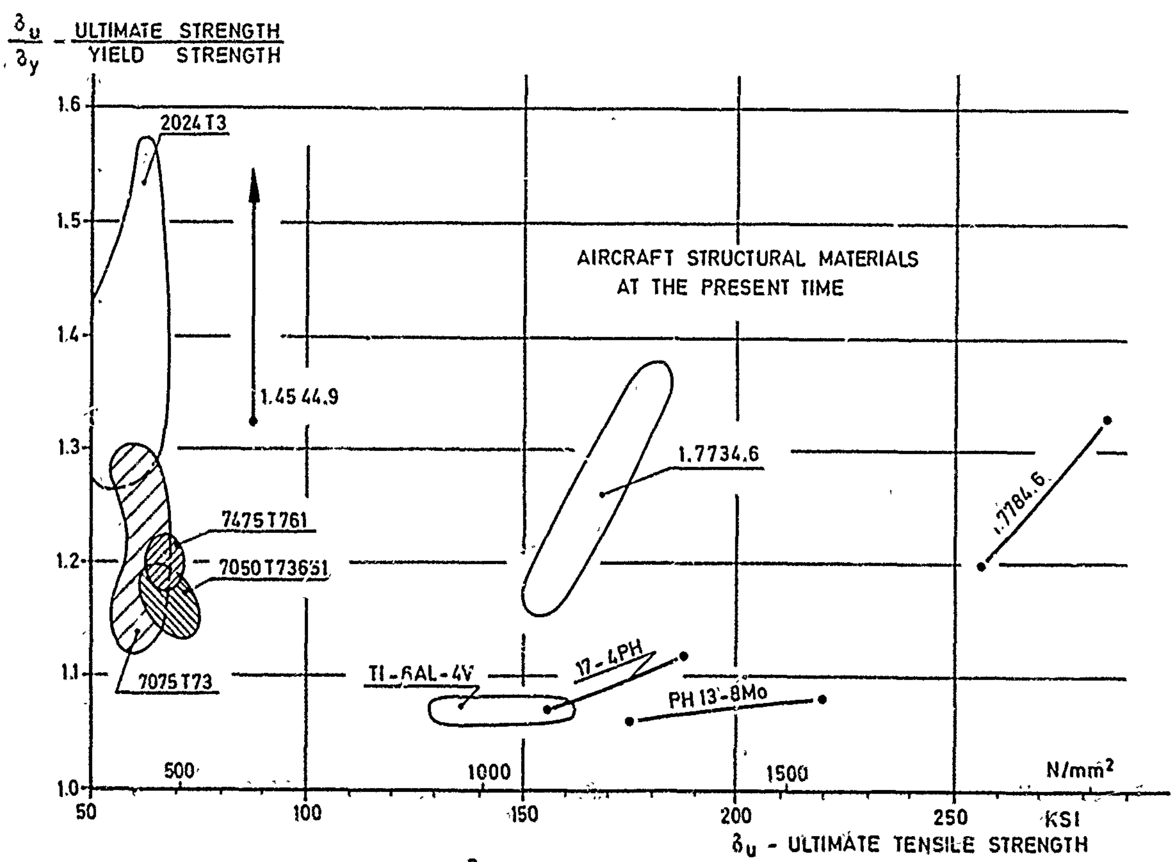

FIG.4 VARIATION OF δ_u/δ_y WITH TENSILE STRENGTH

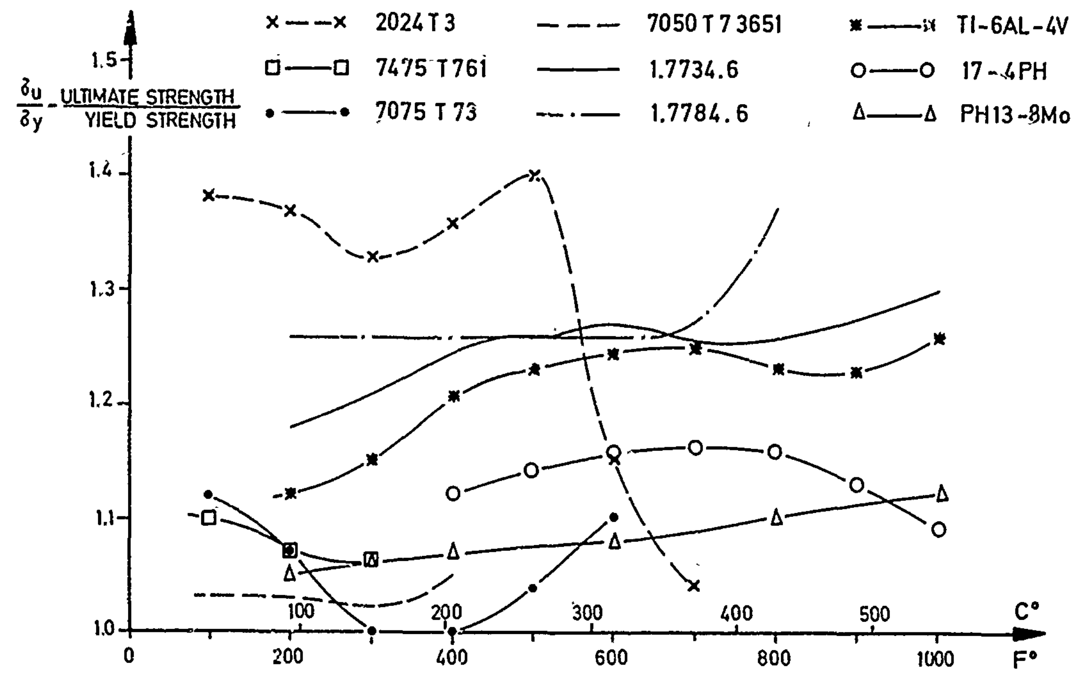

FIG. 5 VARIATION OF δ_u/δ_y WITH TEMPERATURE

Fig. 4 shows the dependence of ultimate strength/yield strength on ultimate tensile strength of some structural materials used today in aircraft construction at room temperature. Fig. 5 shows the dependence of this ratio on temperature. These figures show that the high-strength aluminum alloys, high heat treat steels and titanium alloys in current use have a considerably smaller ratio of ultimate to yield strength than 1.5. It should however be kept in mind that within certain groups of materials toughness decreases with increasing yield strength, an aspect which is important in fracture mechanics consideration.

2.2 Inconsistencies and Deviations

It can be said that in general the present-day safety factor is a more or less arbitrary factor which is multiplied with the limit load or the load factor in order to make sure that prescribed loads may be exceeded by a certain amount before failure of the structure occurs. In general the safety factor also provides for enough strength to avoid permanent deformations due to occurring loads. Limit loads, however, are defined independently of the probability of their occurrence, i.e. safety margins differ according to the type of loading and structural component. Some examples follow:

<u>Limited Loads</u> - For these in-flight loads which are either limited by the capability of the aircraft or by reliable means, the same safety factor is applied as for those whose maximum values are not limited, or cannot be determined within close tolerances. Limited loads are, for instance,

- loads caused by internal pressure (cabin)
- loads caused by control surfaces with limited deflections
- thrust loads of engines or rockets
- loads caused by negative gauge pressures near absolute vacuum
- the occurring load does not have the same safety factor as the main load parameter, as for instance, in the case of up and down gusts (Fig. 6):

(1) Safety factor associated with load factor
$n \times j = j\,(1 + \Delta n)$
up: $= 1.5\,(1+2) = +4.5$
down: $= 1.5\,(1-2) = -1.5$

(2) Safety factor associated with additional load factor
$n \times j = 1 + j\,\Delta n$
up: $= 1 + 1.5 \times 2 = +4.0$
down: $= 1 - 1.5 \times 2 = -2.0$

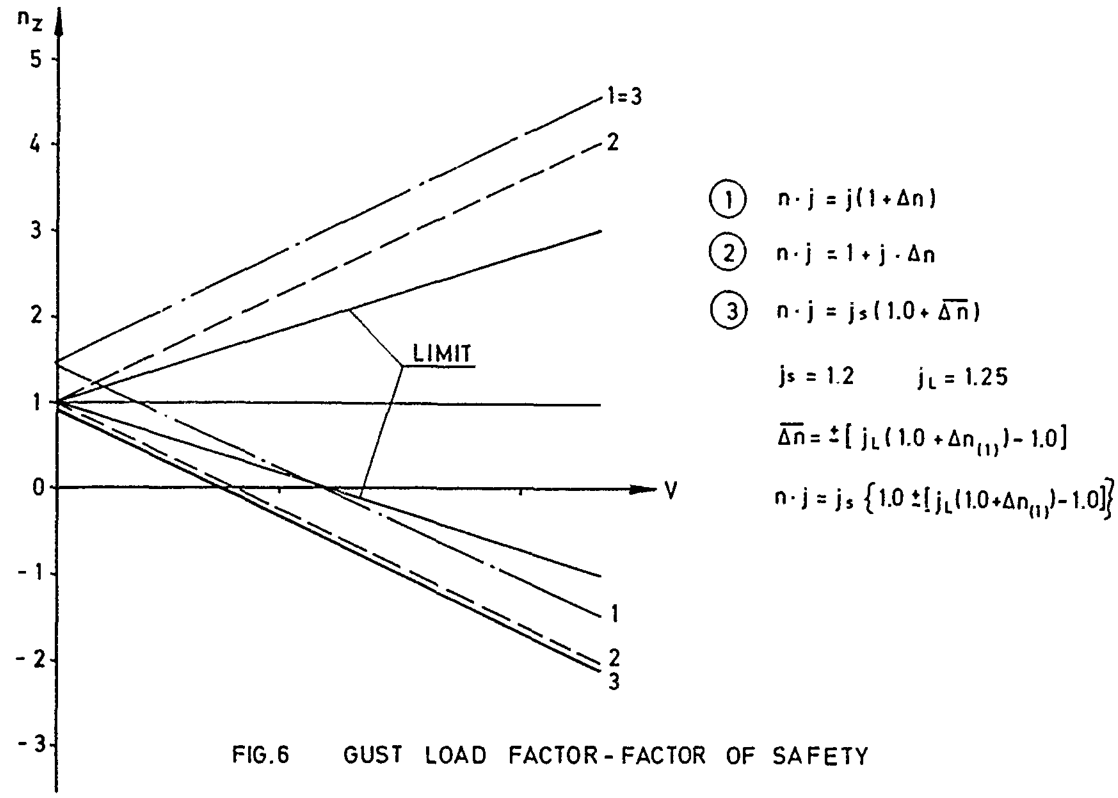

FIG.6 GUST LOAD FACTOR - FACTOR OF SAFETY

In the first case the safety factor is applied to the total load, and yields a ultimate load for the "down-case" lower than that for a gust velocity 1.5 times larger. In the second case the additional load factor is factored out of the gust effect, producing a value for the "up case" lower than that when total loads are considered.

The Dutch aviation agency RLD have stipulated a special requirement for the structural design of a single aircraft type. It raises the ultimate negative gust load factor, as is defined in FAR 25, by $\Delta n = -0.6$. This requirement is derived with the assumption that the safety factor is split into two parts, one for uncertainties in the load, the other for uncertainties in the strength of the material,

$$j = j_L \times j_S = 1.25 \times 1.2 = 1.5 .$$

With this requirement the ultimate negative gust load factor becomes $n \times j = 2.1$ in the preceding example, i.e. somewhat larger than in case 2. Fig. 6 shows the comparison of the two cases, and the RLD requirement, presented as case 3.

2.3 Development of Computation and Test Methods

In the last three decades theoretical and experimental methods of aerodynamics have been developed considerably so that the prediction of aerodynamic forces on structures and their distribution is more accurate than in the past. Virtually all types of in-flight and ground loads can be determined today with the aid of EDP. Calculations also can include the effects of non-linearities and control elements (actuators, dampers, CSAS, etc.). Fig. 7 shows the influence of control components (actuators and CSAS) for a modern fighter during a rolling maneuver. In the past, calculations of longitudinal and lateral motions were decoupled to a large extent because of the large computational effort involved. Today calculations with five of six rigid-body degrees of freedom are quite common.

While in the past, undercarriage loads were determined for each undercarriage separately by associating it with an equivalent mass (unit load), it is today possible to calculate the landing impact dynamically as a whole. Although aeroelastic problems have increased with increasing flight speed and aircraft complexity, the capability to cope with them has, on the whole, increased at the same rate. Here, too, the availability of computers helped to increase the number of degrees of freedom which are used to describe the dynamic behavior of the aircraft. In the field of statics and strength of materials much more detailed stress calculations can and are made thanks to matrix methods, expecially the finite-element method. Advances in experimental techniques concerning measurements and the application of loads to structures also provide a considerably more detailed check on calculations by static and fatigue tests.

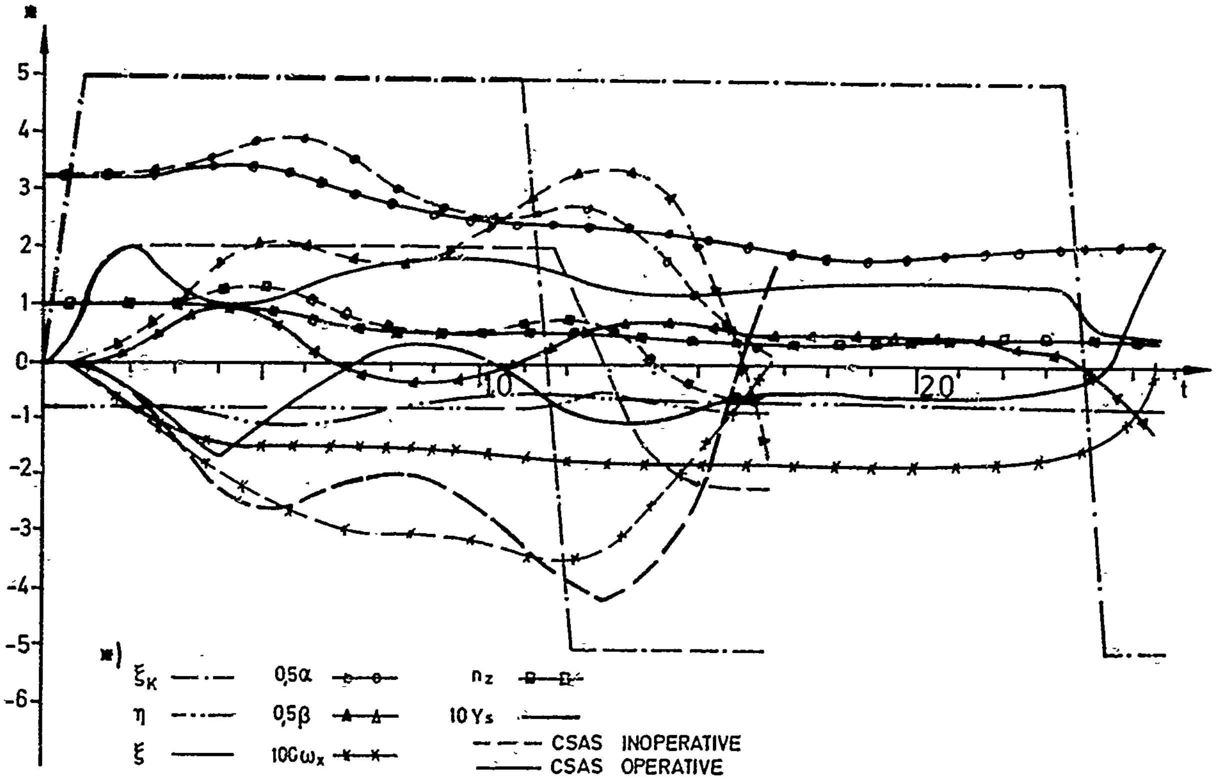

FIG. 7 AIRCRAFT RESPONSE DUE TO AILERON COMMAND

Furthermore flight testing today is in the position of being able to supply a multitude of data because of improvements in the collection, transmission and processing of experimental data. It is, for instance, common practice to measure sectional forces according to MIL-Spec. 8871 at various stations of the structure in flight (several wing cross-sections, at least one empennage section, and one fuselage section). Any significant discrepancies in the measured and the predicted values are then taken into account in the design of production aircraft. A better knowledge of material properties under various conditions (environment), and the ability to test materials and structures non-destructively (X-ray, ultrasonic methods, etc.) makes a comprehensive and thorough quality control possible, beginning with the manufacture of materials and semi-finished products, and ending with the final check of the operational aircraft.

3.0 MAXIMUM LOAD CONCEPT

3.1 Basic Ideas

For the past 20 years the question has been raised by structural experts of various institutions, whether the rather rigid safety factor of 1.5 is still realistic today. This has been documented in numerous publications (see References). One of the alternatives to the 1.5 safety factor that has been proposed is the maximum load concept. The basic ideas of this concept were developed by W. Braun (Reference 11) and J. v. Osnabrugge and N. Schipper (Reference 12). The term Maximum Load Concept was, however, coined later by Aldinio and Tagliaferri (Reference 13).

The main idea of the maximum load concept is to split the proven safety factor of 1.5 into two parts in a rational fashion, one for the uncertainties in the loading (determination of loads, static calculations), the other for uncertainties in strength (scatter of material properties and inaccuracies in construction). Allowable loads are defined as those load values that will only be exceeded by expected loads with a prescribed small probability. These loads are then referred to as maximum loads.

The Airworthiness Commitee of the International Civil Aviation Organization (ICAO) discussed, among other things, the subject of maximum load concept in the period from 1957 to 1970. It was decided in Montreal in late 1970 not to pursue this concept for the time being as a possible basis for airworthiness regulations. Several proposals however, were made to improve structural safety. This subject was also discussed by the Study Group Structures of the AECMA (Association Europienne des Constructeurs de Material Aerospatial) in the context of the Joint Airworthiness Requirement (JAR). These deliberations led to the suggestion to split the safety factor into the previously mentioned two parts, and to consider load limits as maximum loads.

Gust or landing loads are strongly influenced by random physical or human characteristics. But also in these cases safety could be much better defined by extrapolating loads from statistical data, rather than the application of a safety factor of 1.5 for all cases. Loads, furthermore, that are limited naturally by the ability of the aircraft to produce them, or by internal aircraft systems, could be regarded as maximum loads to which a safety factor need not be applied. The determination of maximum loads with a small probability of being exceeded is entirely possible for modern fighters which are limited in their maneuvers, or for control configured vehicles (CCV) which are in any case equipped with a fly-by-wire flight control system.

As a principle the prescribed design boundaries and the corresponding safety factor should not be separated, i.e. the entire design philosophy should be considered. Therefore a mixed application of various regulations to a single project is not advisable. Up to now the safety factor has been reduced in only a few cases. Within the pertinent regulations only the case of the American MIL-Spec. 1960 issue is known, where no safety margin is required for the undercarriage and its supporting structure. It may be supposed that with the consent of the appropriate authorities the safety factor or the load level could be reduced in the following cases:

- in emergencies, such as emergency landings into an arresting net or cable

- for transient phenomena (hammer shock pressures in aircraft inlets)

- where actuators are power-limited and large loads cannot be produced

3.2 Suggested Models

The following models are proposed for the application of the maximum load concept:

3.2.1 Semi-statistical/semi-deterministic

In the past operational loads were predominantly checked by measurement of the main load parameters, in the form of cumulative frequencies or load spectra (Reference 14). They are:

- the normal load factor, in flight and on the ground

- the angle of sideslip and/or the transverse load factor

- the rolling velocity in flight

- the bank angle during landing.

On the basis of these load spectra a probability of occurence of the main load parameters is defined for each type of mission and maneuver, and the maximum value of the main load parameter can be determined from this.

If, for instance, an aircraft is designed for air-to-air combat, a maximum load factor of 9.0 may be derived from the statistical cumulative frequency distribution for every tenth aircraft after 4000 flight hours. This value is taken to be the maximum main load parameter. For this load parameter the loads produced by the maneuvers specified in the pertinent regulations are determined by means of a deterministic calculation such that the maximum value of the main load parameter is just attained, but not exceeded. An example is the loads as a function of time produced by the actuation of cockpit controls according to MIL-8861.

3.2.2 Statistical: Extreme value distribution

As a rule, load spectra are produced with the objective of determining magnitude and frequency of operational loads. These, in turn, are used in vibration tests to determine the corresponding fatigue life of the structure. Load spectra like these are derived from relatively short time records, compared to the actual operational life time; they do not contain those maximum values that might be expected to occur during the entire operational life of the structure, i.e. a knowledge of which is necessary for the design.

In 1967, O. Buxbaum, of LBF, suggested a method to determine design loads from extreme values of frequency distributions (Reference 15). This method is capable of deriving design loads by means of the statistical evaluation of the extreme values, in cases where the range, the maximum value, and the scatter of the spectrum may be safely assumed. The design load determined in this way is described by its magnitude and its probability of exceedance.

As an example the maximum rolling moment at the horizontal tail of the Transall C160 was determined in this way by means of in-flight measurements. The design load was taken to be that maximum value of the extreme value distribution expected to occur once for every tenth aircraft. Figure 8 shows the extreme value distribution for the rolling moment at the horizontal tail for 53 flights. The design load case with $\bar{W}_U = 10\ \%$ for 1250 flights is also shown there, i.e. this rolling moment is expected to occur once for every tenth aircraft within 1250 flights. For purposes of information the values for an exceedance probability of $\bar{W}_U = 50\ \%$ (every second aircraft) and $\bar{W}_U = 90\ \%$ (almost every aircraft) are also shown.

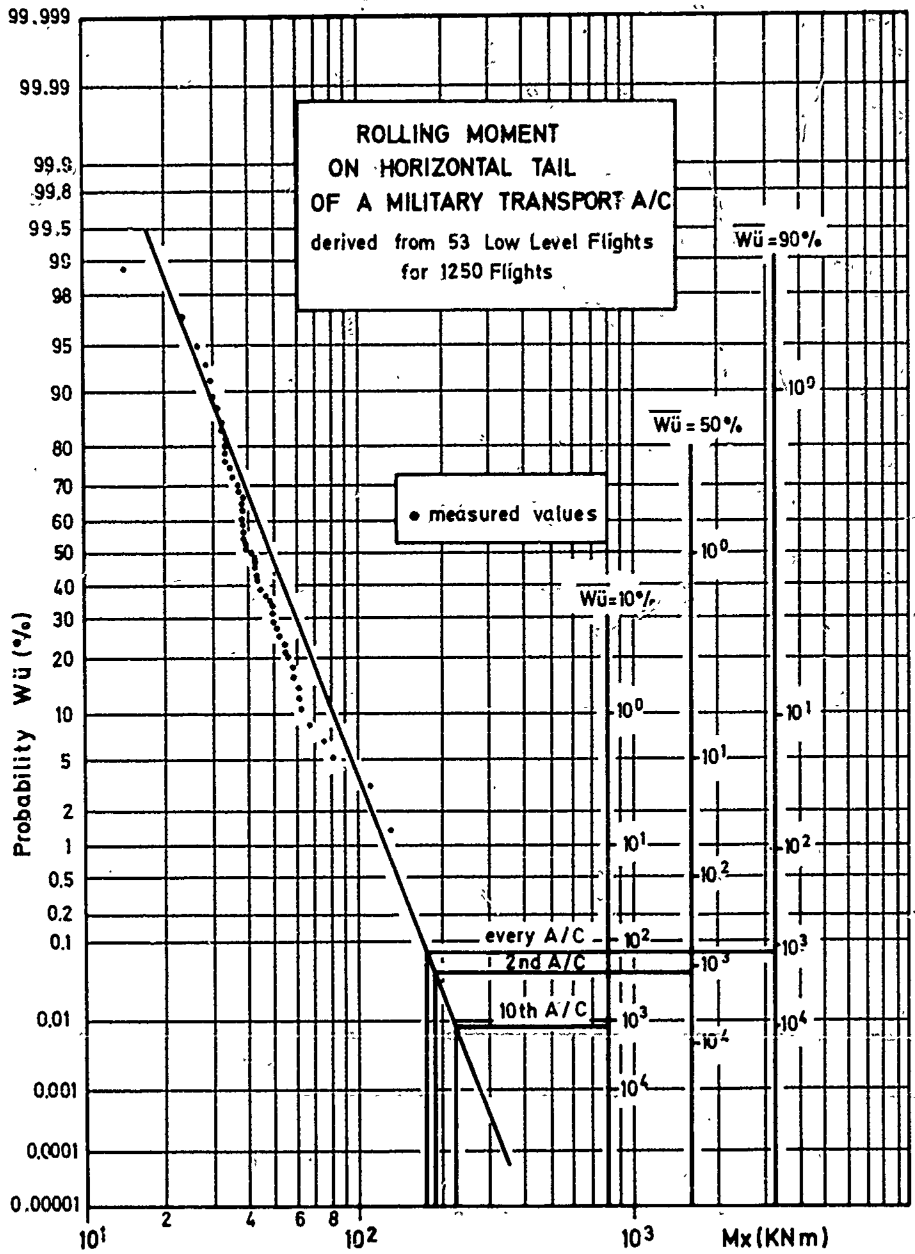

FIG.8 EXTREME - VALUE DISTRIBUTION

The horizontal tail of the C160 was first designed according to the prescribed French AIR 2004/D specification, It requires for the asymmetric loading of the horizontal tail to assume -

- 100 % of the maximum load for symmetric flight cases on one side of the plane of symmetry, and 75 % of this load on the other side;
- in the vicinity of stall, 100 % of the maximum load on one side and 50 % on the other side.

The magnitude of the rolling moment at the horizontal tail, is about twice the moment derived from AIR 2004/D.

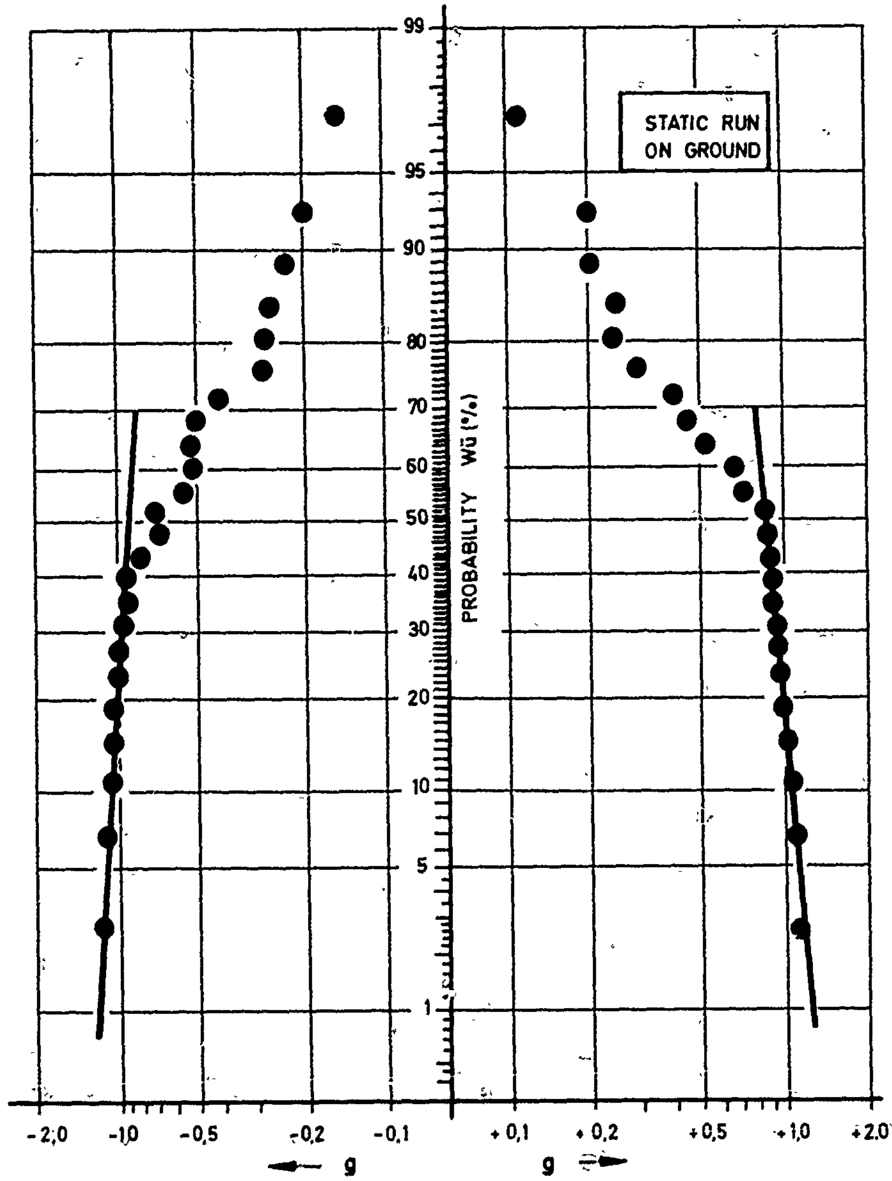

FIG. 9 EXTREME - VALUE DISTRIBUTION VERTICAL ACCELLERATION ON TAIL

In Fig. 9 a further example of the extreme value distribution is shown, i.e., a vertical acceleration on the rear fuselage of the C160 measured in 24 ground runs. This distribution clearly shows the range for maximum engine speed, i.e., the range where almost no rise in extreme values can be detected for decreasing probability of occurrence. Under absolutely equal ground run conditions the extreme values should be independent of the probability $W_{Ü}$, i.e., they could be taken as limited loads.

3.3.3 semi-statistical/semi-empirical

It has been known for some years that VG and VGH measurements do not suffice for the definition of criteria for structural design. In order to obtain statistically supported design criteria, a special NACA Sub-Committee on Aircraft Loads recommended in 1954 to expand statistical load programs to the extent that they included measurements of time histories of eight parameters (three linear accelerations, three angular accelerations, airspeed and altitude). The first measurements of this kind were made with the F 105 D Fighter in peace time with the aim to develop a maneuver load concept which was to predict design loads for the fuselage, wing, horizontal tail, and vertical tail (Reference 16). All data were processed to calculate time histories of loads, with peaks called "observed loads". The data oscillograms were examined in order to define 23 recognizable types of maneuver.

Assuming that for every type of maneuver the same sequence of aircraft motion occurs with the exception of differences in amplitude and duration, the measured parameters were normalized with respect to amplitude and time. Finally, to determine the loads, the normalized parameters were denormalized in order to get the load peak distribution for the wing, the fuselage, and the empennage. The good agreement between observed and predicted load peak distribution demonstrated the feasibility of the maneuver model technique for the F-105 D aircraft.

The F-106 Fighter was selected to demonstrate this model on another aircraft. The detailed results of 3770 flight test hours made it possible to apply the maneuver model technique, i.e. the empirical calculation of component loads as compared to the F-106 design loads (Reference 17). The results in the form of cumulative occurrence of the loads for wing, elevon, and vertical tail made it possible to determine the design load for a given cumulative occurrence.

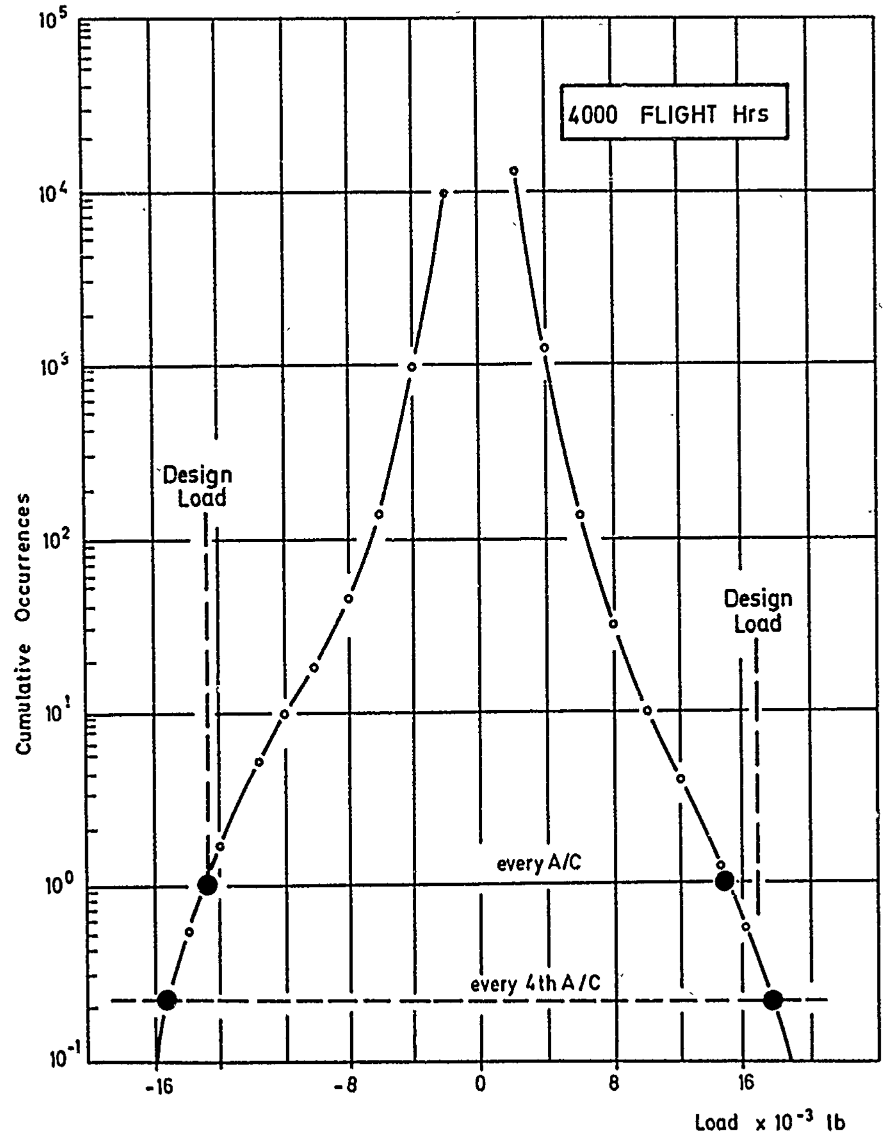

FIG. 10 CUMULATIVE OCCURRENCES OF VERTICAL STABILIZER LOADS

Fig. 10 shows the results for the vertical tail as published by General Dynamics Corporation. It shows how the maximum load for structural strength considerations may be derived from the plots of cumulative occurrence. Two cases are shown there. One is the load that may be expected to occur once in the operational life of every aircraft, the other is the load expected for every fourth aircraft.

3.3 Possibilities of Application

A change in the present safety factor may be considered appropriate, with due regard to durability requirements in the cases of -

Limited loads -

a) loads limited by aircraft internal systems, such as cabin pressure, hydraulic pressure etc.

b) loads that can be determined with sufficient accuracy, or are given within narrow tolerances by design requirements, such as engine thrust, engine inlet pressures, etc.

c) loads that are incapable of being achieved physically, such as those resulting from negative gauge pressures near absolute vacuum, or from aerodynamic boundaries (stall).

Loads resulting from extreme values - Loads which may be derived with sufficient accuracy from measured extreme values.

Aircraft with load alleviation systems -

a) loads which cannot be exceeded in practice by built in limiters, such as bob-weights, shakers, and pushers at the control stick.

b) loads that have been determined for a flight vehicle with automatic control or redundant load alleviation systems (maneuver load control, CSAS, etc.)

Double failures - Loads that have been determined for double failures where an indication of the failure is assured.

4.0 CONCLUSION

The question is raised whether the current factor of safety of $j = 1.5$ still makes sense today. The aim here is to achieve the same degree of safety for all loading conditions. One way to this objective that has already been indicated by structural experts, is to replace the limit load concept by the maximum load concept, i.e., to introduce maximum loads with a reduced safety factor in place of limit loads with a safety factor of 1.5. The main criterion for the design of combat aircraft is given by the maneuver loads. These are capable of being assessed quite accurately at the present time, thanks to the lay out of modern combat aircraft on one hand, and to improved methods of predicting loads on the other hand.

Three possible methods to determine maximum loads are being proposed:

- semi-statistical/semi-deterministic

- statistical: Extreme-value distribution

- semi statistical/semi-empirical

Which of the methods is used depends on the design philosophy for the aircraft in question, and to what extent available statistical data can be applied.

At the present time the life time of an aircraft has become increasingly important in aircraft design. The weight savings due to the application of the maximum load concept therefore should not be overlooked. In fact, the aim here should be to detect inconsistencies within the current concepts and to indicate ways of eliminating them. This may be accomplished by defining and determining design loads individually according to their mission and probability of occurence.

In the field of materials research and construction methods some efforts have been made to develop materials tailored to specific applications and load conditions, and to design structures to take full advantage of new materials. The question is whether even larger uncertainties in the determination of loads are being overlooked. The engineering means of determining these loads exist, but the integration of the body of knowledge and experience in predicting loads could be improved by more systematic studies.

We present these ideas to AGARD, because we feel that if some of these arguments could be incorporated in future recommendations, AGARD would be a suitable institution to make these recommendations to the participating nations. The working methods within AGARD especially, such as the cooperation of the various panels (e.g. SMP and FDP) promise to help attain this objective.

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FACTORS OF SAFETY - SHOULD THEY BE REDUCED?

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SUMMARY

It is now 40 years or more[1] since the factors of safety for fixed-wing aircraft were last adjusted in the UK, USA and Germany, and it is considered timely to review them again. This pilot paper looks at three aspects of the question posed by the title:

a) the prima facie case
b) the probabilistic approach
c) the potential reduction in mass

There is a strong prima facie case, and predicted mass savings for both combat and transport aircraft lend additional support to the argument.

Data is needed to provide a basis for a more representative study of the probabilities of failure; research into this aspect would be very worthwhile.

1 INTRODUCTION

A definition, by referring to basic principles, will often reveal facets of a problem which have been overlooked in the ready acceptance of subsequent interpretations. In seeking a definition of the factor of safety, one is surprised to find that AvP970, the British handbook of Design Requirements for Service Aircraft[2], does not appear to give a definition, although the proof factor and ultimate factor are mentioned in Chapter 200, and Leaflet 200/3 is devoted to an exposition of the fundamental principles underlying the choice of their numerical values.

The British Civil Airworthiness Requirements (BCAR)[3] carry a definition in Chapter D1-2, para 4.5:

"Factors of Safety (for static strength)

Design factors (proof and ultimate) to provide for the possibility of loads greater than those expected in normal conditions of operation, uncertainties in design and variations of structural strength, including variation of strength resulting from deterioration in service".

This definition is interesting in that it gives some indication of the various aspects which the factor is intended to cover:

Uncertainties in loads
Inaccuracies in structural analysis
Variations in strength properties of materials
Deterioration during service life

To this list might be added:

Variations in build standard between nominally identical components.

An oblique reference to these sources of variability is made in para 7 of AvP970 Leaflet 200/5, which states that due allowance must be made for them if the specified factors of safety are to be regarded as adequate.

In considering the factors of safety, therefore, attention must be given to the five sources of variability listed above, and to any changes in variability which have occurred during the past 40 years. A study of these five sources forms the basis of the prima facie case, which presents an argument for reducing the factor of safety. The effect of such a reduction on the probability of failure is shown in the next section of the paper, whilst the effect on operational mass is given in the later sections.

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*EDITOR'S NOTE

This presentation is a compendium of four papers, suitably edited, which were originally written for the Structures Research Sub Committee of the Society of British Aerospace Companies.

2 THE PRIMA FACIE CASE[4]

2.1 Loads

At the time when the ultimate factor was last adjusted (from 2.0 down to 1.5, circa 1935), no flight load data collection had been made to substantiate the basis for the manoeuvres, gust encounters, etc, defined in the requirements. Aerodynamic load distribution diagrams were based on simple lifting surfaces of fixed geometry, and no allowance was made for elastic distortion or for dynamic effects.

It is reasonable to assume that modern load prediction methods, coupled with a better understanding of the flight envelope, should predict applied forces to a higher standard of accuracy than the methods of yesteryear.

2.2 Structural Analysis

Probably the greatest change in the design process during the past 20 years has been the introduction of the computer for structural analysis. The earlier analytical methods, involving over-simplification of the structure to idealise it as a system of beams, struts, ties and shear webs which were amenable to mathamatical treatment, have been largely supplanted by finite element techniques giving a much closer approximation to the true state of affairs. The computer has not been used to speed up the old methods; it has made possible a new approach to structural analysis, and this fact should be recognised when reviewing the factors of safety.

As a counter-argument it should be noted, however, that for many years it has been the practice in the UK and elsewhere to confirm the structural analysis of the major airframe components by means of a static strength test, usually taken to destruction. Any surplus strength has usually been absorbed by developing the aircraft, eg by specifying a greater payload, whilst any strength deficiency has been remedied by local modification.

Since this practice applies whether or not a refined structural analysis has been used, the final outcome is the same; namely that the major components of the aircraft have a fairly uniform reserve factor as near as possible to unity. The only components not proved by structural testing are secondary items such as trailing edges, undercarriage doors and fairings together with some internal structure such as light wing ribs.

2.3 Material Properties

Materials for aeronautical use have always been subject to a strict quality control, and it is doubtful if any credit can be claimed for improvements in this area. Moreover, the introduction of B values has already effectively taken account of a reduction in the factors of safety in certain applications, such as fail-safe structures.

2.4 Deterioration during Service Life

Structures are now expected to survive service lives far in excess of those anticipated even a few years ago. Corrosion, wear, loosening of fasteners and distortion due to mishandling must all be considered, and none of these sources of deterioration has decreased in severity over the years.

However, the official requirements make it clear that the ultimate factor is sometimes set at a high value as a safeguard against fatigue (eg BCAR, where for pressure cabins an ultimate factor of 2.0 is required and as high as 3.0 is recommended). This attitude towards fatigue is somewhat outmoded, and it would be more in keeping with modern philosophies if all static strength calculations were based on a factor of safety which excluded fatigue considerations. The reduction of working stresses to ensure the necessary fatigue resistance is nowadays regarded as a separate, but nonetheless important, operation, and it cannot be achieved by the application of an arbitrarily inflated factor applied to the static design cases.

2.5 Build Standard

The past decade has seen the widespread introduction of numerically-controlled machines for the production of wing skins, spars and ribs; automatic riveting machines for the attachment of stringers; close-to-form forgings; premium quality castings and a stricter control of processes of all kinds.

These improvements in quality have led to a reduction in variability between nominally identical components which should be reflected in a reduction of the factors of safety.

2.6 Potential Reductions

Of the five listed sources of variability, at least three -

Load prediction
Structural analysis
Build standard

have shown improvement over the past 25 years or so, and these improvements should be considered when reviewing the factors of safety.

Two sources have shown no improvement -

Material properties
Deterioration in service

but allowance has already been made for an improved statistical assessment of material properties through the introduction of B values.

3 THE PROBABILISTIC APPROACH[5]

3.1 Instantaneous Probability of Failure

It has been demonstrated by Hooke[6] that at a given time in the life of a structure the instantaneous probability of failure may be obtained if probability density distributions of structural strength and of applied loading are available. (See Fig 1). This probability is compounded from the conditions of load exceeding strength and is clearly dependent upon the shape of the "tail" portions of the intersecting probability density diagrams, together with the ratio of the mean values of the load and strength as given by the ultimate factor (assuming a reserve factor of unity).

A pilot calculation has been performed assuming a normal distribution (for the convenience of available tabulated properties) for both the load and strength probabilities, and the same value of standard deviation in each case. For an ultimate factor of 1.5 it was found necessary to assume a minimum value of the standard deviation of 0.052 x mean, so as to remain within the available data range (max of 4 standard deviations from the mean value). Fig 2 shows the resulting variation in probability of failure per flight against ultimate factor, assuming no structural deterioration with time. The assumed distributions give a large increase in probability of failure as the ultimate factor is reduced.

Using more representative statistical data on aircraft loading and strength gives less severe trends. Dr A.O.Payne, a co-worker of Hooke at ARL, has applied the above approach using probability density data derived from manoeuvre load statistics and from structural strength statistics on major aircraft components[7]. Payne's curve of probability of failure against ultimate factor is included in Fig 2, showing a marked difference in gradient from the "normal distributions" curve.

3.2 Cumulative Probability of Failure (Constant Strength Structure)

The pilot calculation was continued to determine the cumulative probability of failure against number of flights, initially assuming constant strength structure. The Theorem of Total Probability gives the probability of at least one failure in n flights:-

$$P = 1 - (1 - p)^n$$

Where p = constant probability of failure per flight.
Since p is of small order the expression simplifies to:-

$$P = np$$

Applying this equation to the data from Fig 2 gives the curves of cumulative probability against number of flights and ultimate factor shown in Fig 3. The main array of curves is from Payne's work, but also shown for reference are the lines corresponding to the assumed normal distributions in the pilot calculation, again illustrating the sensitivity of these calculations to the input data.

3.3 Cumulative Probability of Failure (Deteriorating Structure)

The final stage of the pilot calculation was to consider the effects of structural deterioration towards the end of the service life. A safe-life design was considered, using data on residual strength against life presented by Payne[8] and assuming a service life of 3000 flights. At a given ultimate factor (intact structure) the variation in mean strength during the period of structural deterioration was expressed in terms of a progressive reduction in the ultimate factor to a value of 1.2 at the end of the life (AvP970 residual strength requirement = 1.2 x limit load). Payne's data was adapted to produce curves of mean residual strength against life (see Fig 4) for various ratios of final residual strength to intact structure ultimate strength. The cumulative probability of at least one failure shows a rapid increase during the period of structural deterioration as shown in Fig 3 for various values of the ultimate factor.

The effect of the specified mode of structural deterioration vis a vis non-deteriorating structure is illustrated in Fig 5, which shows the cumulative probability of at least one failure in the service life of 3000 flights. The figure shows clearly how the residual strength requirement governs this probability and illustrates the diminishing returns obtained from an increase in the ultimate factor. It is interesting to note that the existing ultimate factor of 1.5 gives a reasonable balance between the probabilities for the intact and deteriorated structures (ratio 1:3).

3.4 Future Possibilities

The above exploratory exercise indicates the potential of the statistical approach as a means of rationalising the determination of ultimate factors. It is, however, clear that the results of this type of analysis are very sensitive to the data input, in particular to the probability density distributions of loading and strength and to the shape of the structural deterioration curve.

In the case of the probability distributions there is the problem of obtaining adequate statistics of rare events in the "tail" portions of the curves.

In the case of the structural deterioration curves the variation of residual strength with time will depend upon the damage tolerance philosophy and structural configuration and materials employed.

The possibility of achieving a weight saving by a reduction of the ultimate factor is of course attractive, but must be considered in terms of the increased cumulative probability of failure and of changes in the presently accepted margins between limit, proof and ultimate loads. These margins themselves should be rationalised on a consistent statistical basis with the probability density distribution of loading used in the above calculation.

4 SENSITIVITY OF COMBAT AIRCRAFT MASS TO CHANGE IN ULTIMATE FACTOR[9]

4.1 Procedure

Three typical combat aircraft configurations were examined: delta wing, fixed wing, and variable geometry wing aircraft (aspect ratios: 1.9, 3.5, 7.0 respectively).

The study was in two stages. In the first stage, the reductions in safety factor were obtained by reducing the ultimate factor progressively from 1.5 to 1.0 and the undercarriage vertical descent velocity was reduced by a corresponding amount. Design diving speed and maximum Mach number were kept constant, although an allowance was made for reducing the safety factor in areas designed by local dynamic pressure, eg intake ducts, fuselage access panels.

The resulting reductions in mass were then re-iterated to produce the maximum savings possible on the unscaled aircraft.

In the second stage, the procedure was the same as in the first stage, but the aircraft were completely re-sized within the constraints of the relevant computer program.

4.2 Assumptions

Stage 1 -

- (a) Aircraft size unchanged
- (b) Constant fuel and payload
- (c) Constant power plant

Stage 2 -

- (a) Constant wing loading at combat
- (b) Constant fuel fraction at combat
- (c) Power plant scaled to give constant thrust/mass ratio at combat
- (d) Fuselage geometry scaled to match changes in power plant size and fuel requirement
- (e) Constant tail volume
- (f) All fuel carried internally
- (g) Aircraft balance maintained by insertion or removal of fuselage "plugs"
- (h) Stiffness criteria ignored.

4.3 Results

Tables I, II, and III show the results obtained at the end of the second stage. The results are quoted as percentages of the combat mass for the datum aircraft with an ultimate factor of 1.5.

TABLE I

DELTA WING AIRCRAFT

	UF = 1.5	UF = 1.25	UF = 1.0
Wing	9.4	8.9	8.5
Tail unit	0.7	0.7	0.6
Fuselage	15.3	14.1	13.0
Undercarriage	6.8	6.2	5.7
Total Structure	32.2	29.9	27.8
Propulsion	17.1	16.6	16.0
Equipment	21.5	21.4	21.3
Mass Empty	70.8	67.9	65.1
Payload and combat fuel	29.2	28.5	27.7
Combat mass	100	96.4	92.8

TABLE II

FIXED WING AIRCRAFT

	UF = 1.5	UF = 1.25	UF = 1.0
Wing	9.6	8.2	7.1
Tail unit	1.7	1.6	1.5
Fuselage	16.0	14.5	13.2
Undercarriage	6.7	6.0	5.4
Total Structure	34.0	30.3	27.2
Propulsion	16.8	15.9	15.2
Equipment	22.5	22.4	22.2
Mass Empty	73.3	68.6	64.6
Payload and combat fuel	26.7	25.7	24.9
Combat mass	100	94.3	89.5

TABLE III

VARIABLE GEOMETRY WING AIRCRAFT

	UF = 1.5	UF = 1.25	UF = 1.0
Wing	16.7	12.7	9.7
Tail unit	1.8	1.7	1.5
Fuselage	14.9	13.1	11.7
Undercarriage	6.6	5.6	4.9
Total Structure	40.0	33.1	27.8
Propulsion	14.4	13.1	12.1
Equipment	21.8	21.4	21.1
Mass Empty	76.2	67.6	61.0
Payload and combat fuel	23.8	22.1	20.8
Combat mass	100	89.7	81.8

Figures 6 and 7 show the relative sensitivity of each configuration to variations in ultimate factor.

4.4 Summary of Mass Savings

The results indicate that significant mass savings can be obtained by reducing the ultimate factor, but no account has been taken of the effects of such a reduction on fatigue life and development potential.

Significant savings can, however, only be achieved by continuing the exercise into the second stage, ie by re-sizing the aircraft. The full effects of reducing the ultimate factor of safety can thus only be realised if the aircraft is designed ab initio with the reduced factor.

5 SENSITIVITY OF TRANSPORT AIRCRAFT STRUCTURE MASS TO CHANGE IN ULTIMATE FACTOR[10]

5.1 Objectives and Terms of Reference

The Trident 3B was selected as a typical civil airliner. The objective was to obtain the change in the total structure weight of the aircraft due to a reduction in the ultimate factor. Design limit loads, including the effects of structural flexibility, were taken as unchanged. The reduction in factor applied to all static design cases.

The stiffness, minimum fatigue crack free life and damage tolerance design requirements and aims were not changed, nor was the HSA "in-house" ultimate factor of 3.0 on pressure loads alone for static strength of pressure cabins, for parts designed by tension or shear loads (eg pressure bulkheads and floors).

The only mass savings derived in this exercise were for those component parts designed by static strength requirements, eg wing top surface.

All items of the structure were considered, including the non-metallic parts, eg canopy and cabin windows, cabin floors, paint etc.

Particular static strength requirements such as crash cases and bird impact were retained unchanged, as were the specified minimum material thicknesses.

5.2 Trident 3B Basic Weights

	lb	kg
Design take-off weight	150000	68000
Design landing weight	128500	58300
Maximum zero fuel weight	115500	52400
APS weight	83600	38000
Total structure weight	40400	18300

5.3 Structure Mass Reduction

All components of the aircraft were examined under the conditions outlined above, the detailed results with the associated criteria being given in Table IV.

The total structure mass reduction amounted to 1312 lb (600 kg) being approximately 3.5% of the total structure weight.

5.4 Benefits Which Could Accrue from this Mass Reduction

The mass reduction of 1312 lb could be utilised in at least the following four alternative ways:-

a) Increase in payload. 1312 lb = 4% of maximum payload = 6 passengers plus baggage (at 210 lb per passenger).

b) Increase in range with maximum payload. 1312 lb = 165 imperial gallons of fuel.

c) Reduction of wing area to keep the wing loading unchanged:
   Wing loading = 100 lb/ft^2
   A reduction of 15 ft^2 in wing area keeps the wing loading constant

d) Possible omission of the boost engine in the rear of the fuselage.
   Boost engine mass = 660 lb : SLST = 5250 lbf

5.5 Conclusions from this Exercise on the Trident 3B Structure

a) The relationship between structure mass and ultimate factor is 1% mass reduction per 2% reduction in factor, within say a maximum of 10% change in factor.

b) A reduction in factor from 1.5 to 1.4 would mean a change in probability of occurrence of ultimate load from 10-7 per hour to 2 x 10-7 per hour, assuming limit loads have a probability of occurrence of 10-5 per hour.

c) The benefits which could result are such that a reduction in ultimate factor could be actively pursued, bearing in mind the good safety standard achieved in service.

TABLE IV

STRUCTURE MASSES

COMPONENT	STRUCTURE DESIGN CRITERIA	STRUCTURE MASS PER A/C lb	STRUCTURE SAVING PER A/C lb
Wing top surface	Static strength:compression	2764	170
bottom surface	Fatigue,fail safety and down gust strength retained	2712	0
spars	Mainly static strength:shear,tank pressures	2227	130
ribs	Mainly static strength	1356	88
control surfaces	Stiffness,fatigue,static strength, minimum thickness	2779	80
LE, TE structure	Bird impact,static strength	2900	70
	TOTAL	14738	538
Fuselage main shell (skin stringers,frames)	Fatigue,fail safety; 18 swg skin is a minimum in the pressure cabin; static strength	6593	140
pressure bulkheads and floors and main spar frames	Static strength (HSA UF = 3.0)static strength,fatigue loads	3127	164
cockpit and cabin windows	Bird impact;working stress levels retained	1225	0
cockpit and cabin floors		1172	0
doors and surrounds	Pressure,static strength and fatigue	1221	30
floor beams,seat rails	Crash cases unchanged;other static cases exist	1048	35
freight bay floors	Static strength;minimum thickness in part	726	35
other structures (side engines support, U/c support structure fairings,paint)	Static strength,fatigue	1519	60
	TOTAL	16632	464
Tailplane + elevator	Static strength,fatigue,stiffness	2050	80
Fin + rudder	Fin fatigue (side gusts)	1240	30
Main and nose u/c	No mass reductions on wheels,brakes, jacks	5503	200
Engine mountings	Fatigue,vibration,stiffness	282	0
	TOTAL A/C	40400	1312

6 CONCLUSIONS

The prima facie case shows that improved design and production techniques should make a reduction in ultimate factor possible without a corresponding loss in safety standards.

The studies into the sensitivity of aircraft mass to changes in the ultimate factor show a significant trend for transport aircraft. For combat aircraft, the reductions in mass are worthwhile only if the aircraft are re-sized.

The probabilistic approach shows the need for accurate data on which to base the statistical survey. Future research into the possibilities of reduced factors of safety should therefore concentrate on the collection and analysis of this data.

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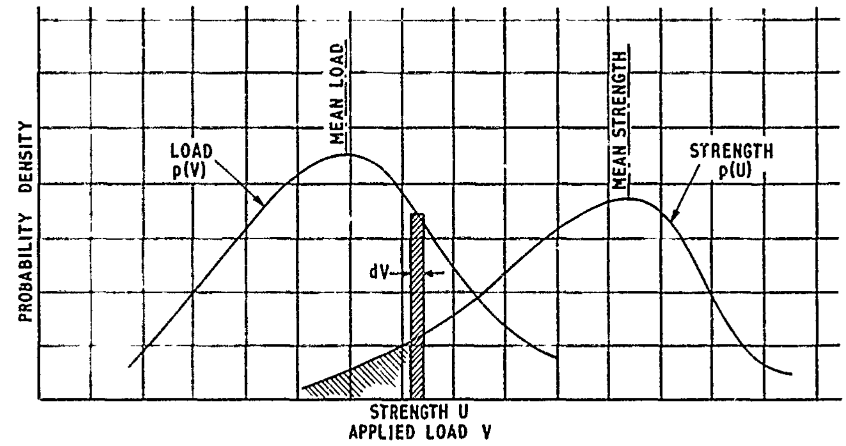

Probability of load lying between V and V+dV is p(V).dV

Probability of strength levels lower than V is $\int_{U=0}^{U=V} p(U).\,dU$

Incremental probability of failure from above probabilities:-

$$\Delta P_c = p(V).dV \int_{U=0}^{U=V} p(U).dU$$

Total probability of failure:-

$$P = \int_{V=0}^{V=\infty} p(V) \int_{U=0}^{U=V} p(U).\,dU.\,dV$$

FIG.1 PROBABILITY OF FAILURE DUE TO LOAD AND STRENGTH VARIATIONS

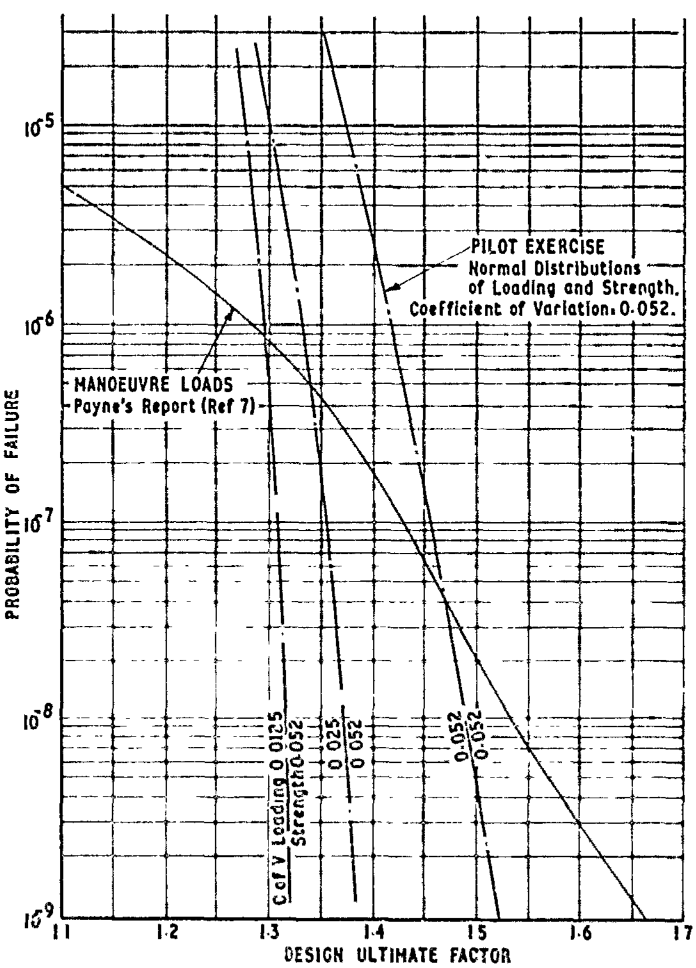

FIG.2 PROBABILITY OF FAILURE PER FLIGHT v DESIGN ULTIMATE FACTOR

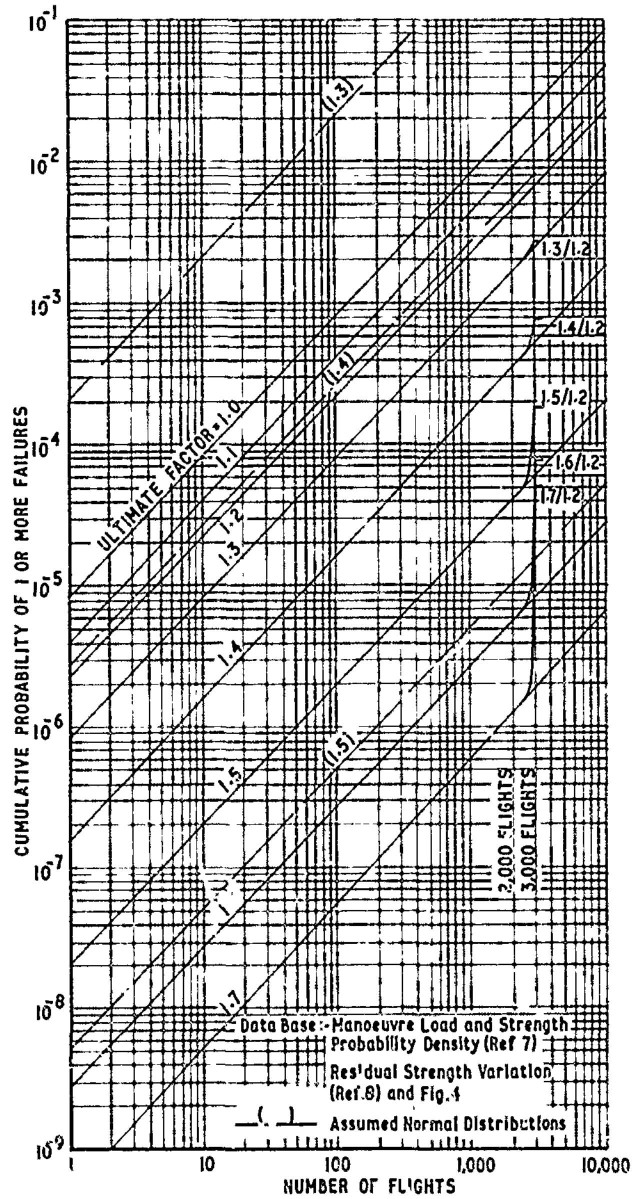

FIG.3 CUMULATIVE PROBABILITY OF 1 OR MORE FAILURES v NUMBER OF FLIGHTS and DESIGN ULTIMATE FACTOR

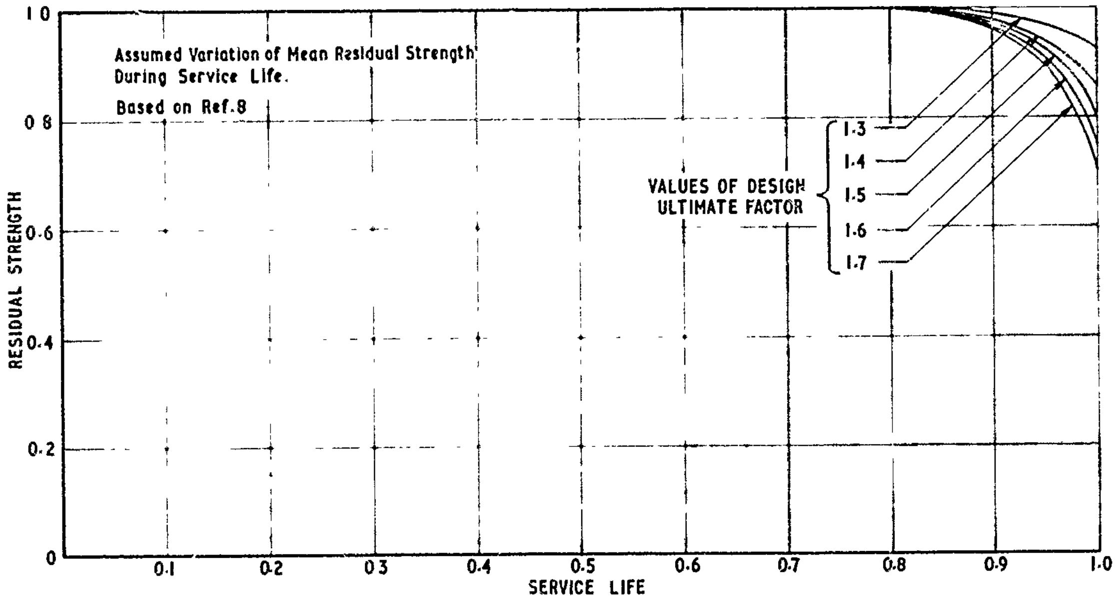

FIG.4 SAFE-LIFE STRUCTURE WITH RESIDUAL STRENGTH AT END OF SERVICE LIFE = 1.2 x LIMIT LOAD

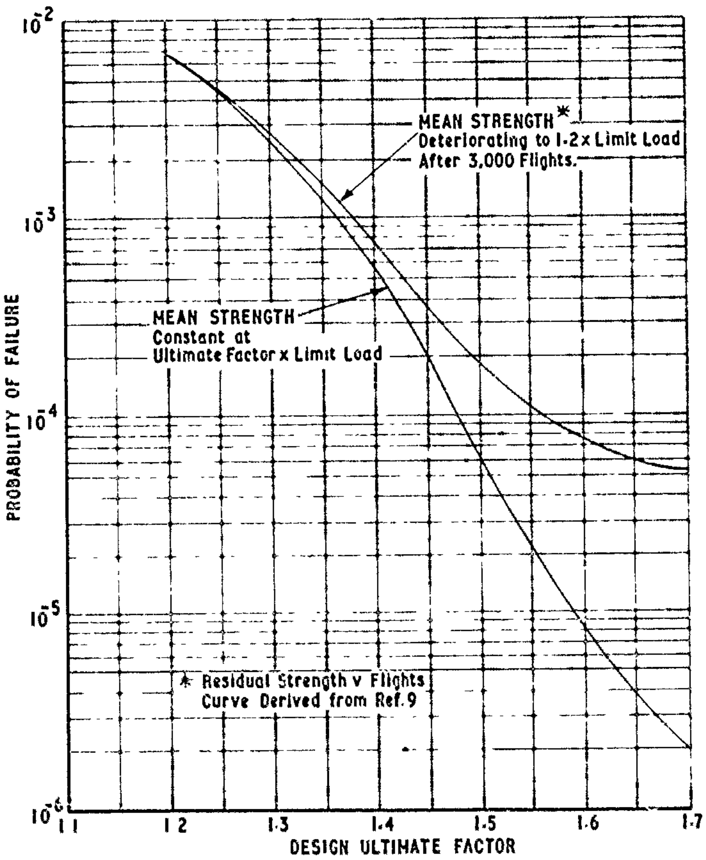

FIG.5 CUMULATIVE PROBABILITY OF AT LEAST ONE FAILURE IN A SERVICE LIFE OF 3,000 FLIGHTS

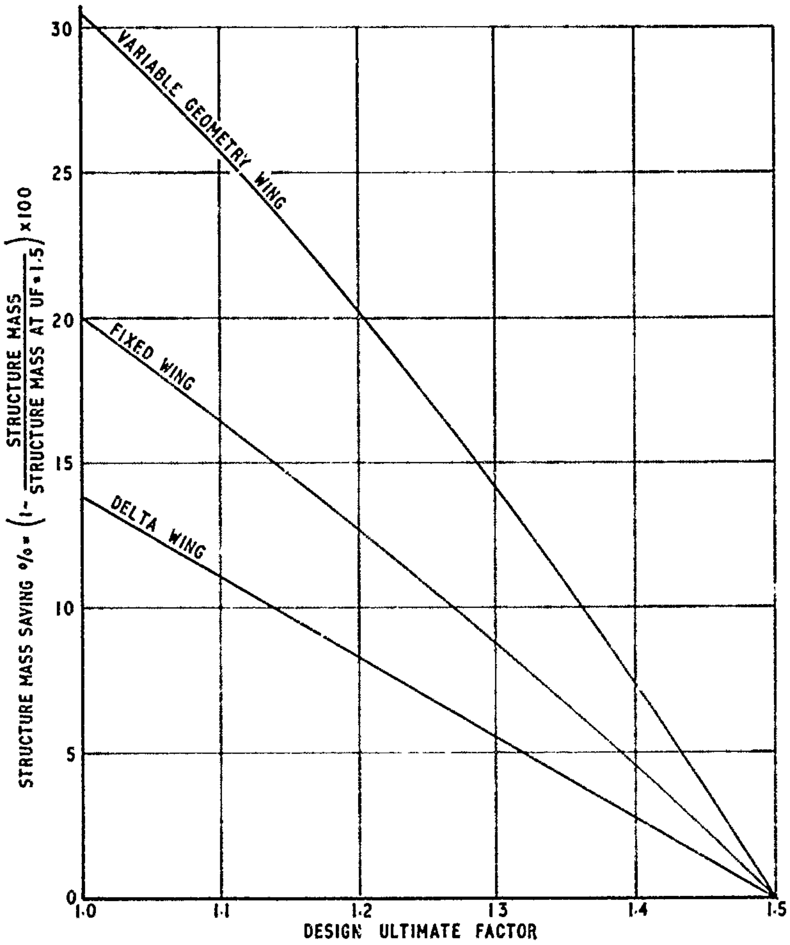

FIG.6 SAVINGS IN STRUCTURE MASS FOR VARIATIONS IN ULTIMATE FACTOR(FULLY RE SIZED A/C)

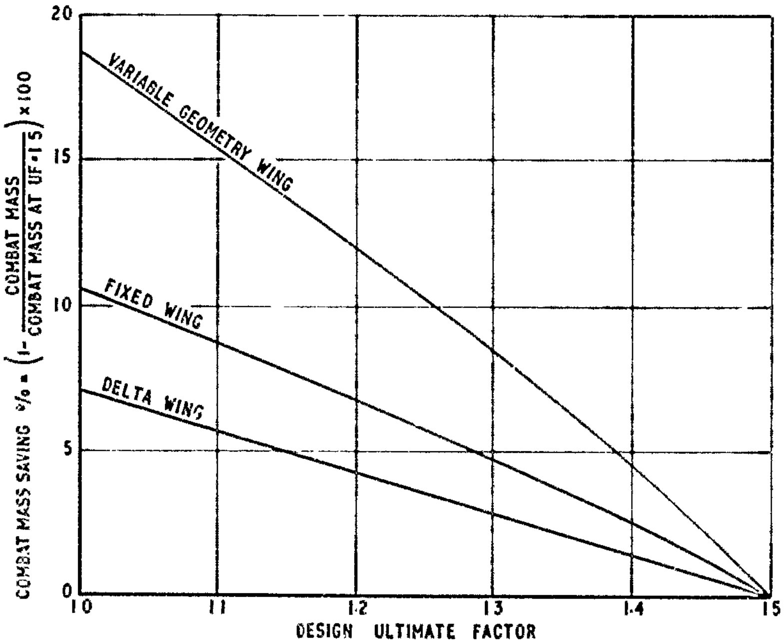

FIG.7 SAVINGS IN COMBAT MASS FOR VARIATIONS IN ULTIMATE FACTOR(FULLY RE-SIZED A/C)

FACTOR OF SAFETY-USAF DESIGN PRACTICE

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ABSTRACT

The 1.5 factor of safety is a highly visible airframe design parameter. The factor is empirically derived and provides an almost universally accepted measure of flight safety. Although the measure is qualitative, the level of safety provided by the 1.5 factor has become an accepted standard. These facts have developed a tendency among engineers to both challenge the continued application of the 1.5 factor of safety for efficient airframe design and yet avoid any change that would challenge the confidence of future designs. The unsettled position on the factor of safety may never completely stabilize but it can be clarified by reviewing its historical significance.

In U.S. design practice the significance of the 1.5 factor of safety can be placed in perspective by reviewing its development for both military and civil use. The factor evolved as a compromise opinion based on flight operations. The approximate 1.5 ratio of ultimate stress to yield stress for certain materials coming into use during the same time period supported the decision but did not influence the selection of the 1.5 factor of safety. Since the time of its selection, variations and adaptations to other aircraft types have been proposed and sometimes used. Several variations and experimental applications are reviewed.

The factor of safety design concept has recently lost some of its appeal and reliability-based concepts have been emphasized. As part of its structural design criteria development program, the Air Force has sponsored investigations to develop reliability-based criteria. Three of these investigations and similarities between the factor of safety and reliability concepts are reviewed. Although the use of reliability-based concepts will probably increase, their application to airframe design may be limited. The factor of safety still covers many contingencies and it appears at this time there will be a continuing need for some factor.

1. INTRODUCTION

From the beginning of flight and even before power was used, the concept of safety was considered. Wilbur Wright, in a letter to his father, Bishop Milton Wright, on September 23, 1900, wrote the following:

> "I am constructing my machine to sustain about five times my weight and am testing every piece. I think there is no possible chance of its breaking while in the air."

Early designers, researchers, and pilots were interested in safety and were anxious to establish facts and information identifying maximum loads on various parts of the airplane. Wind tunnel measurements made before and after 1900 were used principally to predict airplane performance rather than structural strength, but in-flight loads measurements to assess strength were also made during those early days. To this day, occupant safety is a primary concern in designing manned vehicles and the "factor of safety" has become a prominent design concept.

The historical development of the 1.5 factor of safety in U.S. practice is largely unknown, even among the engineers who use the factor frequently. Although not without criticism, little if any thought or concern is given to using the 1.5 factor in day to day design applications. This fact would seem to reflect its basic acceptance. This is not true, however, with other structural design requirements which are frequently challenged and modified. Design specifications and practices are continuously reviewed and revised.

A concerted effort to "rationalize" airplane design requirements took place during the 1930's as a joint effort between the Army, Navy, and Civil Aeronautics Administration. The development of the 1.5 factor of safety is closely related to, and interacts with this "rationalization" effort. The term "rational" in this case refers to a logical rather than an arbitrary requirement.

The improvements that evolved were the result of a better understanding of actual airplane operations as they occurred during the 1920's and of the various parameters which influenced design loads and load factors. For example, Reference 1 states that during the mid-1920's a particular formula for computing the load factor capability of an airplane was not used by U.S. designers, since flight tests had shown this formula to be unreliable. The state of knowledge at that time provided more information about the actual maximum loads that could be expected in flight than were known about the parameters used in the formula, therefore limiting its effectiveness. However, as a result of continuing flight and ground tests, and engineering studies, overall knowledge grew quickly and the "rationalization" of earlier requirements could be seriously considered.

Although structural design requirements tend to change frequently, the 1.5 factor of safety, as adopted and applied to design loads, has not changed. When design or operational problems arise or structural failures occur, certain corrective changes are usually made to the design specifications, load prediction techniques, manufacturing techniques, environmental standards, or operational restrictions of the airplane. No known official action has ever been taken to increase the 1.5 factor of safety. The only known attempt to change it would have reduced the factor, which has always been treated in a relatively independent manner with respect to other design and operational criteria since its adoption.

Specific references relating to the origin of the 1.5 factor of safety are almost nonexistant. Like many design requirements, the utilization of the 1.5 factor of safety evolved over a period of time and it is not an independent development. The interaction of engineering and operational experiences are documented under unsuspecting titles that do not allude to their historical relationship with the 1.5 factor of safety.

There was a reasonable, although not exhaustive, search of the open literature for information relating to the history of the 1.5 factor of safety, but there were no directly related references found. Fortunately, several related articles were already known and were readily available. Those few associated references that were found are related to the "new" interest in "rationalizing" structural safety on a reliability basis. This interest began in the late 1950's and early 1960's. It is concerned almost entirely with replacing the current 1.5 factor of safety with probabilistic interpretations of structural safety. Certainly, today's technology can better handle the mathematical and computational aspects of a more complex safety evaluation and may have prompted the current interest.

Variations to the conventional factor of safety and probabilistic techniques that have been considered and used by the USAF, as they relate to static structural strength, will also be reviewed to show how they evolved and are related to the 1.5 factor of safety.

The history of the 1.5 factor of safety has already been documented by two of the people actually involved with the formulation of design requirements during the 1920's and 1930's. Mr. A. Epstein worked for the Army Air Corps Material Center from 1929 to 1940 and prepared the original Air Corps Structures Specification X-1803 in 1936. He continued his career in the U.S. aircraft industry working in the structural loads and criteria area until his recent retirement. Mr. F. R. Shanley worked for the Civil Aeronautics Administration in the 1930's and is knowledgeable of the development of civil airworthiness requirements. Another source of civil airworthiness requirements, as they relate to the factor of safety, is a history prepared by the Los Angeles Regional Office of the Civil Aeronautics Administration. These histories are given as References 2 (Military) and 3 (Civil). The history of the 1.5 factor of safety given in this paper is derived almost entirely from these references, which are the only specific sources known to the authors.

2. DEVELOPMENT OF THE 1.5 FACTOR OF SAFETY

The 1.5 factor of safety in U.S. design practice is fundamental, and represents a level of design safety which has become an accepted standard. However, engineers now challenge the continued application of the 1.5 factor for efficient airframe design, and yet tend to avoid any major change in design philosophy that would challenge the confidence of future designs or encourage legal entanglements. The factor currently provides a balance between design efficiency and safety and it's significance can perhaps be placed in perspective by reviewing both its military and civil development. Such a review can be helpful in judging the 1.5 factor's current and future applicability.

The evolution of structural design criteria from the semi-impirical and arbitrary regulations in effect during the 1920's to the relatively rational criteria established by 1940 is found in References 2 and 3. These references are indispensable and will be used extensively to relate the history of the 1.5 factor of safety in this section.

In the early 1920's, the U.S. Army Air Service maintained as a contractual document for design, the Handbook of Instructions for Airplane Design (HIAD). Mr. Alfred S. Niles, in his book "Airplane Design" published by the Engineering Division of the U.S. Army Air Service in 1926 (Reference 1), detailed the structural criteria found in the 1925 edition of the handbook. The handbook criteria, although adopted independently, was the result of a four year effort to obtain identical design rules by the Army and Navy. In most cases, agreement was reached.

Civil airplane design practice paralleled the development of military practice. Civil air regulation began in 1926 and requirements were published in Aeronautics Bulletin No. 7-A, "Airworthiness Requirements of Air Commerce Regulations." The bulletin was kept up to date by periodic revisions and was replaced in 1938 by Part 04 of the Civil Air Regulations, in keeping with adoption of the Civil Aeronautics Act of 1938 (Reference 3a).

The Army and Navy specified design load factors for three flight attitudes, as shown in Figure 1. Two of these, low and high incident (angle of attack) attitudes, were associated with dive recovery initiation, and final recovery from a pull-up to maximum load factor. The low incident dive attitude with its aft center of pressure usually designed the rear wing spar. The associated design load factor, which was two-thirds of the high incident value, was based on a lift coefficient of one-fourth the maximum lift coefficient. This was a realistic design concept at the time, considering the relatively limited speed range of the airplanes and the reduced lift coefficient at the low incident design point. The range of speed from stall to maximum was sufficiently restricted that when a high load factor maneuver was performed, the airplane would generally come close to the maximum lift coefficient. To achieve the same maximum load factor at low incidence, where the lift coefficient was one-fourth the maximum, twice the speed would be required. Such a speed could not be achieved and thus, the reduced factor was realistic. The third flight attitude for which design load factors were specified was that of inverted flight.

Civil airplane design load factors were originally based upon actual acceleration measurements during Air Corp tests in the early 1920's. To avoid establishing categories or weight classifications for various airplane types, the load factors were made dependent on airplane gross weight and power loading. Until 1932 load factors were given in chart form using these two variables. These load factors were modified slightly in 1932 for airplanes having low power loadings. The requirements in Bulletin 7-A were revised in 1934 to include certain basic performance and design characteristics by using empirical equations based on previous operational practice. Although the load factor charts were known to neglect important airplane characteristics, such as wing loading and drag, no substantial changes were made in the maneuvering load factors themselves. The load factor charts were replaced in 1934 by an empirical equation and the minimum design load factor was reduced from 4.0 to 3.75 because of satisfactory experience with large flying boats (Reference 3a).

The term "factor of safety" was recognized in a general sense, but various interpretations were applied. During the 1920's and early 1930's, all loads were ultimate and airplanes were designed to load factors which varied for each type. Reference 1 defines factor of safety as the ratio between ultimate load and maximum probable load. It states that the least factor of safety used for airplanes is usually 2.0 and that the term "factor of safety" is often used incorrectly in place of the term "load factor." A nearly identical definition for factor of safety was in use in Bulletin 7-A in 1929, and its use may have been the result of Mr. Niles' influence (Reference 1). In a minor sense, terminology was a problem and Reference 1 also gave definitions for design load, normal load, ultimate load, load factor, and margin of safety. Similar terms were also defined in the 1934 edition of Bulletin 7-A.

While writing Air Corps Specification X-1803 in 1936, Mr. Epstein noted the ambiguousness of the terms "applied" and "design" and proposed "limit" and "ultimate." The new terms were later adopted in a joint meeting of Army, Navy and Commerce Department representatives, the forerunner of the group that later originated the ANC programs, which are shown in Figure 2. The accepted terms first appeared in the 1940 changes to Specification X-1803.

The first edition of the Civil Air Regulations, issued in 1938, included the same terminology change. The terms "design" and "applied" were replaced by "ultimate" and "yield." Both of the new terms referred to loads required to be withstood by the structure. The term "limit" was also introduced to specify the "actual" or "expected" load factor. The limit load factor represented a flight limitation for which the airplane was expected to be completely airworthy (Reference 3b).

As defined in Reference 1, Mr. Niles seems to have ignored the maximum maneuver load factor capabilities of the airplane in his assessment of the factor of safety of 2.0. He apparently used only the more typically achieved maneuver load factors when assessing the difference between actual and design loads. There were no flight restrictions to limit maneuvers, for example, to half the ultimate design load factor (to insure a factor of safety of 2.0) and it was characteristic at the time to use the more typical (or average) maneuver load factors as a basis for design regulations. The Civil Aeronautics Administration during the same period specified only a load factor value (ultimate) in the order of 6.0 for a typical airplane. The implication was that the airplane structure should not fail before reaching 6.0G in flight. There were no maneuver load limitations specified but there was the assumed factor of safety of 2.0.

During the 1920's, operational flight load factors began to increase. In 1921, Reference 4 stated that a load factor of 4.5 was sufficient for stunting based on flight tests using a JN-4H airplane. The Air Corps, in flight tests conducted in 1924, recorded a load factor of 7.8 in a PW-7 airplane flown by James Doolittle. This factor was the highest reached and occurred during a sharp pull-up at 162.5 mph (Reference 5). The 7.8G compared to the theoretical maximum of 8.15G at C_L max and a design factor of 8.5G. The 7.8 load factor certainly could not be considered in the "maximum probable load" category when considering the factor of safety definition in Reference 1, but rather as an improbably high load. Similarly, the thought that airplanes had an approximate factor of safety of 2.0 was more of an opinion which was based on limited operational data and not on aerodynamic capability. Pursuit airplane design load factors were increased to 12 when it was realized that the 8.5 design load factor then in effect could be readily exceeded.

In 1927 (Reference 6), a Navy F6C-4 airplane developed a load factor of 10.5G during a pull up and in 1930 (Reference 7) a PW-9 pursuit airplane reached accelerations up to 9G during flight load test programs. Both of these airplanes were designed to ultimate load factors of 12G. However, there were no further increases in pursuit airplane design load factors as a result of these experiences.

The Army, Navy and CAA began during the early 1930's to "rationalize" their design requirements. The objective was to relate the air loads more closely to actual flight conditions. This effort eventually resulted in the introduction of gust loading conditions, airplane speed, the V-G diagram and the use of aerodynamic derivatives. A number of the more significant milestones in the evolution toward rational criteria are described in Reference 2c. The 1.5 factor of safety evolved from this "rationalization" process as an outgrowth of the flight test programs conducted.

The formal introduction of a factor of safety of 1.5 into Air Corps requirements occurred in 1930 but it only applied to establishing design tail loads. The H1AD (handbook) design loads for the horizontal tails at that time were admittedly arbitrary and insufficient for the expected service of many airplanes. Reference 8 established a new method which consisted of determining the steady-state flight path and speed of the airplane with zero power, assuming a complete range of angles of attack from maximum positive to maximum negative. The balancing tail load was then computed for each of these points. The balancing tail loads so defined were further adjusted by a velocity factor and increased 50 percent for design. The 50 percent factor over the computed load was termed the factor of safety for material. The adoption of this design technique also introduced the use of airplane speed and aerodynamic derivatives (wing moment coefficients) as requirements.

The flight loads program reported in Reference 7 was the most comprehensive undertaken up to that time (1930). It was conducted at the request of the Air Corps to determine the magnitude and distribution of loads over the wing and tail surfaces of a PW-9 pursuit airplane during maneuvers most likely to impose critical loads. The maneuvers included pull-ups, rolls, dives, and inverted flight. Pressure distributions and load time histories were recorded. The distributed loads measured over the tail surfaces were two-thirds of the design loads and assuming that the factor of safety of 2.0 applied, the report concluded that the design load criteria should be increased. The same data in Reference 7 were again evaluated in Reference 9. In Reference 9, the authors assumed that the maximum operational loads were the specified ultimate design loads divided by a 1.5 factor of safety. The measured tail loads actually were about two-thirds of the design values and helped to substantiate the 1.5 assumption, although it was a weak assumption in a statistical sense. It was their belief that the requirements were based on "an anticipated load factor plus a margin of 50 percent to allow for possible imperfections of material, approximations of analysis and general lack of knowledge of loads." In Reference 7 and 9, then, we see two conclusions based on the same data. Each "conclusion" occurred by assuming a different factor of safety.

Although some disagreement and possible confusion seemed to exist, it could have been worse. Presumably, if the 2.0 factor had been considered the norm, the 12G PW-9 airplane should not even have been permitted to exceed 6G. If the highest 9G load factor recorded by the PW-9 airplane had been considered and compared to the 12G design load factor, an even lower 1.33 factor of safety could have been assumed when evaluating the flight data in Reference 7. Now consider again the factor of safety of 2.0. If it was still the accepted norm as assumed in Reference 7, then the "new" conclusion in Reference 9, that a 1.5 factor of safety prevailed during flight operations, was not adequately supported. The assumed need for a factor of safety of 2.0 in 1925 was just as valid as assuming the 1.5 factor existed in flight operations in 1931. Neither value could be substantiated statistically. Clearly, a change in thinking had occurred as a result of operational practice and available flight test data.

Mr. Epstein notes in Reference 2c that his thinking followed this pattern. In the early 1920's a factor of 2.0 was considered necessary as implied in Reference 1 by Niles. In the late 1920's, actual operational flying of the newer airplanes were coming closer to the ultimate load factor than earlier models. Airplanes were flying up to two-thirds and more of the ultimate load factor and nothing was happening to the structure; therefore, the evolution of thinking toward a lower factor of safety was a natural one.

Mr. Shanley expressed similar thoughts in Reference 3a. He favored using a 1.5 factor of safety to keep the permissible limit loads relatively high, as compared to a factor of 2.0. Although a requirement relating limit loads to the absence of permanent set had not yet been written, Mr. Shanley interpreted limit load at that time as not exceeding yield strength.

As summarized by Mr. Epstein in Reference 2c, the factor of safety was considered a variable which depended upon the sample of flight data used, and personal judgement as to the bases to be used in assessing the factor. In terms of actual strength, there was no way of knowing a true factor of safety in view of the limited knowledge of loads and stress analysis.

At this point in time, a factor of safety philosophy had essentially evolved, but had not been formalized. Airplanes were flying at two-thirds of ultimate load factor, permanent set was not desirable, permissible limit loads should be as high as possible, and a 1.5 factor was already in use to establish design tail loads. Yet, there was no formally established relationship between design load factor, maximum aerodynamic maneuver capability and operational maneuver limits. These relationships would evolve with the development of the V-G diagram.

The concept of a V-G diagram that defines the design boundaries of an airplane is generally attributed to Richard Rhode. Prior to the adoption of this concept, the factor of safety had limited significance. The diagram itself appears obvious and elementary but it represents a major milestone leading to rational criteria. The Navy Bureau of Aeronautics was the first to specify this diagram, shown in Figure 3, as a requirement in 1933.

In the interest of establishing standardized design requirements with the Navy, the Air Corps had initiated a study of the Navy series of criteria specifications (Reference 10) in May 1933. The result of this study is found in Reference 11. Much of the diagram's development effort evolved around the definition of the upper left and right hand corners of the envelope. The Navy had specified rounded corners. An existing Air Corps requirement called for the maximum load factor to occur at maximum lift coefficient and therefore recommended that the maximum acceleration and maximum lift coefficient line form the upper left hand corner. This point was adopted. For consistency, the lower left corner was made the intersection of the negative maximum lift coefficient line and the negative design load factor. The Air Corps also recommended that the upper right hand corner be a right angle to provide a definitive low angle of attack design point.

To counter the argument that airplanes performed satisfactorily in service with reduced load factors for this low incidence (angle of attack) corner, Mr. Epstein noted that stress analysis was inherently conservative and the structure was actually stronger than analysis indicated. Further evidence to justify a right angled upper right-hand corner was provided by data in Reference 12 where a P-12C airplane was shown to have initiated a pull up from a vertical dive, starting at 250 miles per hour. A maximum speed of 255 miles per hour was reached and a maximum load factor of 8.5 was developed (at low angle of attack) at 248 miles per hour, which was only a slight reduction from the maximum speed.

Maximum speeds were already defined for design purposes as either the terminal velocity in a vertical dive, which was applicable for pursuit airplanes, or as a restricted speed given in a percentage of high speed. These speed definitions were also used to form the maximum speed line for the V-G diagram. The upper and lower right hand corners were finally adopted as right angle intersections of the maximum speed line and the maximum positive and negative acceleration lines. With the adoption of the V-G diagram, the tail load requirements of Reference 8 became obsolete because airplanes were then required to be balanced for all points of the diagram.

The maximum design load factor boundary of the V-G Diagram had in essence already been established. The precedent not to design to the maximum aerodynamic capabilitites of an airplane had already been established in Reference 9, which states that, "If the attempt is made to design present service pursuit airplanes to take care of the highest accelerations so far observed, 10.5G, and still retain a factor of safety of 1.5, the ultimate design load factor would have to be raised to 15.75." This high factor was felt to be unwarranted by virtue of the accompanying weight increase and loss in performance. Therefore, the principle of not designing to the maximum recorded load factors was recognized and the maximum load factor boundary for the V-G diagram was established by the load factors then in use.

Having agreed on the boundary of the V-G diagram, the question of how to use the diagram in conjunction with the factor of safety as a design and operational boundary remained to be resolved. The Army and Navy differed in opinion as to whether the V-G diagram should be an ultimate or a limit diagram. The Navy V-G diagram represented an elastic limit requirement. Yet the limit was difficult to define because the Navy did not have a fixed factor of safety. Appendix II of Navy Specification SS-1 (Reference 10) states that the ratios of ultimate strength to elastic limit strength should be equal to or greater than 1.35 for all conditions except the dive, in which case the factor is to be a minimum of 1.5. Wing cells were to be designed to any point within the V-G diagram without exceeding the elastic limit of any structural member and the horizontal tail had to sustain the maximum balancing load multiplied by 1.5 without permanent set, and by 2.0 without failure. The Navy also had a flight V-G diagram and a requirement that the flight loads should not exceed the elastic limit of the structure. Appendix II suggested a factor of 1 05 or 1.10 as the flight elastic true (yield) factor of safety.

The Air Corps study in Reference 11 recommended the adoption of a single factor of safety as a preferable alternative to the variety specified by the Navy. Since an Air Corps precedent for using a

1.5 factor of safety had already been established, it was recommended that the 1.5 factor be adopted for the V-G diagram. However, the Air Corps also recommended that the V-G diagram be an ultimate rather than a yield diagram as the Navy had been using it. The Air Corps proposed flight limits were to be two-thirds of the ultimate factors shown by the diagram.

This design philosophy was incorporated into Revision 6 of the HIAD, dated March 1934 and the 1.5 factor of safety became a formal Air Corps requirement. The use of an ultimate V-G diagram was later changed by the Air Corps to a design load factor diagram in August, 1936, when Specification X-1803 was issued. Based on available records, the reason for this change in thinking is not clear. Apparently the original concerns leading to the recommendation of an ultimate diagram must have been alleviated.

The original concern that led to the ultimate V-G diagram recommendation was related to the secondary non-linear bending load effects with load factor found in the wing spars of biplanes and braced monoplanes. An explanation of this concern is given in Reference 1 and relates to a DH-4 wing test as reported in McCook Field Serial Report 2391. The report concluded that wing spars should have sufficient lateral bending strength to prevent a tendency to twist under some wing loading conditions. To prevent lateral spar failure, the strength requirement for the internal wing drag truss was increased 33 percent. The Navy engineers disagreed with those of the Army regarding the need for the additional factors and did not adopt them.

When Specification X-1803 was issued, this and additional drag truss design requirements were given as part of the Wings and Wing Bracing classification (Figure 4). To insure torsional rigidity, the design requirements for internal wing truss designs were increased as a function of the wing type and ranged from a factor of 1.33 to 3.0. These factors were used in addition to the 1.5 factor of safety. The change in thinking by the Air Corps, in going from the ultimate V-G diagram to the design load factor diagram, seems to be related to a desire to standardize with the Navy, and a feeling that the additional design factors would provide the desired strength. A possible third consideration may have been the inherent advantages associated with using common envelope limits for both design and operational purposes.

The Aeronautics Bulletin No. 7-A retained the previously described factor of safety philosophy and the implied value of 2.0 until 1933. The 1934 revision involved a correlation of loading conditions with actual flight conditions and it was necessary to redefine the design or "ultimate" load factor. An "expected" or "actual" load factor was defined in conjunction with the ultimate load factor and a factor of safety The ultimate load factor was divided by the factor of safety to obtain an "applied" load factor which was not allowed to cause any permanent structural deformation. The actual strength requirement in the 1934 issue of Bulletin 7-A stated that, "The minimum factor of safety for any aircraft structure or component therefore shall be 1.50 unless otherwise specified. This requires that the ultimate strength of any member shall be at least 1.50 times as great as its critical applied load" (Reference 3b).

Over the years, some writers have attributed the origin of the 1.5 factor of safety to the characteristics of the newer 2024 aluminum (24ST at that time). It had a ratio of ultimate to yield stress of approximately 1.5. Actually, the precedent of a 1.5 factor of safety (for design tail loads) had already been established when the Air Corps formally adopted it for overall structural design. Mr. Epstein has stated in Reference 2c that material properties were not an Air Corps consideration. If they had been, 17ST, which was the aluminum alloy used at the time, would have dictated a factor of safety of 1.7, since it had an ultimate value of 55,000 psi and a yield value of 32,000 psi. The corresponding value of 4130 steel which was widely used at the time is 1.2. The 1.5 ratio for the newer aluminum, although not a direct influence on the decision to use a 1.5 value, did support the selection.

There were also opinions, as noted by Mr. Shanley in Reference 3a, which attempted to relate airplane operation and permanent set of the structure, or a lack of it, to the selection of the 1.5 factor of safety. This is often cited as the basic reason for the choice of 1.5 rather than some other number. The approximate 1.5 ultimate to yield stress ratios of commonly used materials and the apparent lack of permanent deformation appeared to mean that airplanes had not been developing more than about two-thirds of their design load factor in flight. Mr. Shanley points out that he was not convinced that the permanent set philosophy was a "sound argument, for at least two reasons: (1) It did not apply to compressions members that failed by buckling, and (2) tension members were almost always critical at joints, for which the efficiency was generally below 80 percent." As previously cited, Mr. Shanley's main reason for favoring a 1.5 factor was to allow limit loads to remain relatively high (as opposed to the assumed factor of safety of 2.0). Since he also interpreted limit load as a requirement to preclude permanent set during normal operations, he concluded that the only significance to be placed on the two-thirds ratio was that it imposed no penalty on existing airplanes when working backward from existing load factors, using a factor of safety of 1.5.

From the point of view of the Air Force, the history of the 1.5 factor of safety can best be summarized by several of Mr. Epstein's observations. In Reference 2a, Mr. Epstein noted that the decision by the Air Corps to stipulate a 1.5 factor for subsequent design in conjunction with the V-G diagram was supported by, and not the result of, the fact that the 24ST Aluminum alloy material then coming into use had a 1.5 ratio between ultimate tensile and yield strength. He felt that the adoption of the 1.5 factor of safety was much more significant (than any coicidental association with material properties), in that, its adoption in conjunction with the use of the V-G diagram recognized "the principle of an airplane being limited operationally to a flight envelope within which it would not experience any significant permanent set."

He further notes in Reference 2c that, "the factor of safety of 1.5 has withstood many moves to alter it, but there was a period in 1939 when the Chief of the Structures Branch of the Engineering Division at Wright Field thought seriously of reducing the value of the factor. Newer aluminum alloys were becoming available with higher ratios of yield to ultimate strength, and he interpreted the factor as the ratio of ultimate to yield. However, no action was taken when the following explanation was offered: 'The factor of safety is not a ratio of ultimate to yield strength, but is tied in with the many uncertainties in airplane design, such as fatigue, inaccuracies in stress analysis, and variations of material gages from nominal values. It might also be considered to provide an additional margin of strength for an airplane subjected to shellfire.'"

Finally, Mr. Epstein notes in Reference 1a that, "In subsequent years there have been various assessments made as to the significance of the 1.5 factor of safety but actually its origin (in USAF requirements) was an opinion of what was representative of service flight operations."

The 1.5 factor of safety remains today in an intermittent state of assessment. Its use in U.S. airplane design practice has never been formally designated as a fixed design entity or as a single design entity, although it is often viewed in that sense. Other important structural design factors affect safety, but they are normally viewed in a less rigid fashion. Each factor that has evolved is applied in a specific way. The 1.5 factor applies to the basic external ground and flight loads while other supplemental factors apply, for example, to pressurized cabins, castings and fittings. The size of the safety factors selected usually depend on the design application, manufacturing standards and the intended operational use of the airplane which existed at the time they were adopted. Since circumstances change, a review of the origin of each factor is always of interest and worthwhile. Perhaps this review will help place the significance and future applicability of the 1.5 factor of safety in proper perspective.

The remaining sections will discuss the history of other well known factors of safety and variations to the factor of safety design concept from an Air Force perspective.

3. DEVELOPMENT OF OTHER FACTORS OF SAFETY

As seen in the previous section, the 1.5 factor of safety did not evolve as the result of a concerted effort to derive a useful factor. It evolved together with other design requirements as part of an overall desire to rationalize structural design criteria. Other commonly used factors of safety also "evolved" in a similar, but more direct fashion than did the 1.5 factor of safety for airplanes.

The history of the 1.25 factor of safety for missiles as a requirement is relatively complete. The factor evolved as part of an overall effort by the Army, Navy and Air Force to develop strength and rigidity requirements for missiles. The derivation of the actual value of 1.25 which finally evolved is not as well defined, however, at least with regard to Wright Field records. The value seems to have evolved through a philosophical trial and error process. Missile strength and rigidity requirements, including the 1.25 factor of safety, were formally published by the Air Force and the Navy in Specification MIL-M-8856 (ASG), which was dated 22 June 1959.

Missile design requirements were actively pursued by both the Air Corps and the Navy but they were preceded by those of the pilotless airplane. In 1945, the Air Corps compiled requirements for such vehicles. The document, "Stress Analysis Criteria for Winged Missiles," did, in effect, apply to pilotless airplanes and was derived from Specification C-1803-12. This specification retained the airplane factor of safety of 1.5. The Navy wrote a "General Specification for the Design and Construction of Pilotless Aircraft," in April, 1949. This document was referred to the Aeronautical Standards Group (ASG) by the Navy in December, 1949. A letter from the ASG to the Chief of Ordinance (Pentagon), recommended coordination of the specification with all branches of the services.

In 1952, a tri-service Guided Missile Task Group was formed by the Office of Standardization, Defense Supply Management Agency. The task group was composed of five subcommittees, one of which was to prepare structural criteria and data requirements. This subcommittee first met in January, 1953. The Navy wrote the first draft of a guided missile strength and rigidity specification for the Criteria Subcommittee in February, 1953. This draft specification required a 1.15 factor on yield strength, a 1.5 ultimate factor for loading conditions hazardous to personnel or to the launch airplane, and a 1.0 ultimate factor for all other loading conditions.

The Air Force, prior to this time, had been using a variety of ultimate safety factors including 1.0, 1.15, 1.25, 1.30 for its winged and ballistic missiles. Occasionally, more than one factor was used on the same missile as occurred on the Matador. The ultimate factor changed from 1.15 to 1.25 between early designs and the "B" model. At the time the above Navy draft specification was written (1953) the Air Force had already informally established the 1.25 ultimate factor of safety as a standard value for missiles. This difference in Air Force and Navy factor of safety philosophy became very evident by the third meeting of the Criteria Subcommittee and the factor of safety became the most controversial issue to be resolved.

The matter was "resolved," as noted in the next draft specification, by deleting the use of any specific factor of safety and allowing each user of the specification to insert their own value. This approach to the factor of safety disagreement appeared in what was termed the "final draft" of the specification in June, 1954. However, the actual finalization of the specification draft took considerably longer.

The Army had initially participated with the Air Force and Navy during the first few meetings of the committee but did not attend after October, 1953. The Army Ordinance Corps felt that the state-of-the-art did not warrant the issuance of a specification at that time. They did, however, submit comments on later drafts when they were circulated for coordination. The committee's final draft did not circulate for formal coordination until July, 1955, and all activities were terminated in March, 1956. The remaining tri-service coordination activities were assigned to the Navy Bureau of Aeronautics, Director of Standardization.

Changes continued to be made to the "final" draft and several iterations evolved. In the June and December 1957 drafts, the factor of safety was reinstated but in a different form than had been used previously. A choice was given to the user. He could select factors of 1.0 yield and 1.33 ultimate, or 1.15 yield and no ultimate factor. Why this choice of factors was inserted and why the 1.33 was selected is not clear from available Air Force records. The 1.15 factor was a standard Navy yield design factor and originally recommended for missile applications by the Navy, as previously stated. The 1.33 value was a common factor used for pressure vessel designs, which was a major design aspect for many missiles. The apparent intent was to allow reasonable design trades between structural components which were designed principally by pressure considerations and those that were not.

A revision to the December, 1957 draft, dated September 1958, revised that factor of safety to 1.0

for yield stresses and 1.25 for ultimate stresses. This represents an apparent change in Navy design philosophy. The 1.5 ultimate factor was retained for handling and flight launch design conditions. The December, 1958 draft and the final published specification retained these factors which are still in use today. Although MIL-M-8856 was published in final form as an Air Force-Navy specification, the Army still retains an interest in it and is kept informed when revisions are made.

The most interesting aspect of the missile specification is not the formal introduction of the 1.75 factor of safety to structural design, but the introduction of probabilistic design techniques. The specification requirements stipulated that "all combinations of loads and loading conditions having an acceptable probability shall be considered." A specific requirement was included for the design limit incremental gust response on a reliability basis. A probability of exceedance was stipulated for the design of air-to-air, surface-to-surface and surface-to-air missiles. Structural load responses to gusts were to be derived from the method found in NACA TN 4332 (Ref 13) and a definition of the atmosphere in power spectral density form was taken from NACA Report 1272 (Ref 14). The probabilistic gust requirements replaced the original discrete gust requirements found in early drafts of MIL-M-8856. The earlier discrete gust requirements were patterned after airplane requirements and were vigorously objected to by the aircraft industry. The industry also emphasized the need for a common atmospheric description for the design of the structure and the control system. Probabilistically defined wind and gust descriptions were included in the final specification.

In all, an extended period of time was required to develop, coordinate and issue the original MIL-M-8856 (ASG) missile specification, but many of the requirements were new and never before formally coordinated between the Services.

A related side light is the development of the 1.4 factor of safety which is used for manned space vehicles. This factor originated within the Aircraft Laboratory, Wright Air Development Center (WADC). The factor was defined by the same office responsible for all other Air Force airplane and missile criteria (Reference 15). The 1.4 factor grew out of a laboratory study to evaluate the applicability of the 1.5 factor of safety for large separable boosters for manned space vehicles.

The Dyna Soar (X-20), manned maneuverable reentry system, was under development at the time and the booster systems were an integral part of the development. The manned glide re-entry vehicle was being designed by the 1.5 factor of safety, but the factors applicability to the booster was questioned. The laboratory study considered the usual design, construction, and manufacturing limitations and interactions, but the material properties provided the major weighting factor. The ultimate to yield stress ratios for the two candidate Dyna Soar booster materials were nearly identical. To maximize structural safety and efficiency, the material characteristics were reviewed and safety factors were chosen to bring the design working stress closer to the design yield stress. Because of the uncertainty related to the design of large, integral pressure vessels in combination with flight loads and temperatures, a 1.1 factor on yield was selected in combination with a 1.4 factor on ultimate. The study conclusions emphasized that high safety factors and high reliability, are not necessarily equivalent, nor do they negate the problems of inadequate design practice or analysis, ineffective quality control or prevent brittle material failures. The yield and ultimate factors were to apply to all combined aerodynamic, inertia, pressure, and thrust loads for both the solid and liquid propellent boosters then being considered. The liquid booster propellant tanks, however, when subject only to pressure loads, were to be designed to a 1.25 ultimate factor because the internal pressures were considered more predictable than those in a solid propellant booster.

The 1.4 ultimate factor of safety, as initially developed, was intended for a specific vehicle design, the X-20 booster. It was not intended for broader application or to be used without the 1.1 factor on yield stress. Its use established a precedent, however, and it has since been quoted in many publications. Presumedly, the two factors are still considered applicable to current designs, as they have since appeared in both Air Force and NASA design requirements for manned space vehicles.

Currently, both missile and space vehicle structural design philosophies are factor of safety oriented. However, the overall design requirements for these vehicles are more closely related to a reliability-based criteria than are current airplane designs. In the next section, other basic concepts which relate to both airplanes and missiles will be reviewed. These concepts will include modifications to the conventional factors of safety, and certain reliability-based criteria interactions.

4. FACTOR OF SAFETY DESIGN CONCEPTS

The desire to "rationalize" design criteria has never ceased. Structural design requirements (Military Specifications, for example) are in a constant process of review and revision. Because of its encompassing influence on structural design, the factor of safety has received considerable attention in recent years. This attention, though, relates primarily to the factor of safety as a design concept. The specific value of the factor of safety is usually a secondary consideration. The actual value does not readily equate to a specific level of safety, and it is difficult to judge the difference in safety as related by a change in factor from 1.5 to 1.4, for example. Similarly, the factor of safety concept does not readily equate to an identifiable design objective that provides or defines structural integrity. Integrity is achieved through many interacting design facets, some of which are obvious and some abstract. The concept primarily provides a "safe" operating margin between an operational and design level of strength. Just how "safe" this margin makes the airplane is always open to question because of numerous unknowns and parameter variations which affect structural loads, design, analysis, materials, operation, and the natural environment. Because of these unknowns and variations, the actual degree of structural optimization achieved is also questionable. The apparent high degree of structural integrity achieved by the factor of safety concept is often the result of indirect, intuitive considerations and reactions to previous problems. Design and operational experience has essentially provided the basis for the "acceptability" of current requirements and the "safety" provided by the factor of safety concept. To overcome this apparent lack of precision, definition and objectivity and improved design flexibility, the use of probabilistic techniques and reliability-based design criteria are often proposed.

Having reviewed the history of several well known factors of safety for airplane and missile design in Section II and III, we can now review a number of Air Force studies of variations to these factors and note their influence on current design practice. These variations to current factor of safety design concepts tend to blend with reliability-based concepts. One effectively leads to the other because some of the variations are an attempt to "rationalize" criteria and are intended to be a step toward a reliability-based criteria.

The operational environment has become increasingly hostile, and more and more demands are made of the airframe. To improve airplane performance and accurately appraise structural design requirements, established criteria must be continuously updated and supported by adequate technology. The technical support must include analytical techniques for determining aerodynamic derivatives, vehicle dynamics, heat transfer, stress-temperature distributions, material properties after prior random exposures, a suitable means of qualifying a structure to actual or reasonably representative environments, and a satisfactory means of flight test demonstration. Regardless of the design concept, the parameters that affect the structure and its response must be further explored. A realistic appraisal of our current ability to guarantee the design of a reliable structure and to define the steps required to obtain a reasonable assurance of structural reliability is also required (Reference 16).

Statistics have formed a basic part of airplane criteria from the time that sufficient data were available to judge the reasonableness of values used for maneuver load factor and design gust (Reference 16). Material properties, sink speeds and other parameters used for estimating fatigue life are also derived statistically. However, all current requirements for static strength call for a specific factor of safety to be applied to maximum expected loads even though some of the design parameters and resulting loads were statistically derived.

For about two decades, which span the 1950's and 1960's, two additional design concepts, "safe-life" and "fail-safe," have been used in combination with the factor of safety to design military airplanes for the fatigue or repeated load environment. Chief emphasis has been placed on the factor of safety and safe-life approaches. The fail-safe concept is added to a design when high reliability is required (as in transport airplanes) or when performance penalties are not incurred (as in fighter airplanes). The safe-life concept attempts to identify, through analysis and test, the fatigue critical areas of the airframe and off-set problems which might occur within the specified life-time of the airplane. This presents a "conflict" between the non-probabilistic factor of safety concept and the probabilistic concept of safe service life. Faced with an increasingly complex operating environment and a demand for more reliable (economical) airframes, the designer has attempted to make the most of each concept. The factor-of-safety, a static strength parameter, will not provide for time varying affects, and the safe-life concept suffers from a lack of appropriate operational and structural component test data. Therefore, the task of designing a reliable structure has been to incorporate analysis methods which combine the useful functions of each concept (Reference 17).

More recently the term of "safe-life" has become obsolete and the terms "damage tolerance" and "durability" have been introduced. The design intent to provide structures that are safe and economical to maintain has not changed but the approach is different. The current Air Force design philosophy emphasizes both the damage resistance or tolerance to manufacturing or service induced flaws for some specified period of service usage and the economical maintainance of the airframe.

The term damage tolerance is not new, but the emphasis on assumed initial or service induced flaws in the airframe is relatively new. The damage tolerance concept is intended to minimize catastrophic structural failures due to the propogation of undetected flaws in critical locations. To contain the damage, fail-safe and slow crack growth design concepts are used. The fail-safe concept contains local damage by use of multiple load paths and tear stoppers. The slow crack growth concept protects safety by not permitting flaws to grow through unstable rapid propagation. This is done through inspections, or life limiting in the case of non-inspectable structure.

The durability requirements emphasize low maintenance costs during the life of the airframe. The durability concept is intended to minimize airframe maintenance due to cracks and related structural degradation. The safe-life concept used a factor of 4.0 in predicting fatigue life and was a combined deterministic/probabilistic concept. In essence, the damage tolerance concept (which does not use a directly applied factor) can be considered as deterministic as the safe-life concept because the stipulated initial flaws are in fact, factors of safety on time.

The most argued "advantage" for reducing the factor of safety is the reduction in airplane weight and the accompanying increase in performance. An impressive discussion in favor of reducing the factor of safety to save weight is provided in Reference 18, which was written in 1954. The discussion considers permanent set, allowance for defects in material and workmanship, stiffness, and maneuver load exceedances. Proper accounting of these points during design is shown to support a decrease in airplane weight. The arguments seem factual and are still current. Some facets can be updated to todays design philosophies and technology to further support the contentions given. The advantages to reducing the factor of safety are shown by decreases in gross weight as a function of factor size and proportionate increases in performance for representative military airplanes. Of special interest is the note that airplanes frequently exceed design limit load factors and that such factors may require an increase, rather than continuing to count on the 1.5 factor of safety to cover such occurrences. The projected control of limit load factor exceedances by the use of entirely automatic flight control systems has not materialized for piloted airplanes but is quite common for missiles and space craft.

Reference 18 also points out the erroneous idea that the 1.5 factor of safety always provides an actual operational level of strength 50 percent above limit load factor. Structural design procedures assume a linear load increase between limit and ultimate load when the 1.5 factor of safety is used. Due to aerodynamic nonlinearities, some parts of the airplane reach loading conditions greater or less than 1.5 times the limit load when the airplane achieves ultimate load factor. Operational conditions and related design requirements also impose different strength requirements on specific components at different times. For any one design condition there will be an "imbalance" of strength distribution throughout the airframe. This can be minimized but cost, schedules and the lack of appropriate aerodynamic load data early in design often hinder the development of a more efficient, or "balanced" airframe. Then, again, there are many unknowns regarding the influence that a weight reduction program may have on the airframe in later years, or if the weight savings will significantly improve performance and reduce operational costs.

The significance of reducing airframe weight fractions below current averages in terms of performance, lifetime operational costs, and structural maintenance, is difficult to evaluate. System dependency, the initial level of structural design conservatism, the increasing severity of operational environments, and damage tolerance design requirements further complicate the evaluation. Factual design interactions can be established best when design flexibility is highest, early in design. Yet, factual design and operational usage data are normally not well defined early in design. Weight reduction programs are often conducted "after the fact," concentrate too heavily on reducing only airframe weight, and minimally evaluate the many other less prominant but important performance and design interactions. Although cost savings are often correlated with airframe weight, the probability of actually realizing the theoretical savings shown, or projecting the impact of the "savings" on structural maintenance and reliability, are seldom evaluated. Many of todays aerodynamically efficient airplanes are volume limited, rather than weight limited, when loaded. Hence, the airframe weight saved does not necessarily provide a performance or operational advantage and could possibly be put to better use by improving the durability of the airframe. Unfortunately, very little factual data is available to accurately weigh the validity of these points.

Any change in structural weight is further reflected as an even larger change in gross weight. This relationship is described by a "weight growth" factor which is the ratio of the delta change in gross weight for each one pound change in structural weight. A certain range or value of weight growth factor can be used to describe an airplane category (transport, fighter, or bomber) but a specific factor must be calculated for each airplane to be accurate. Although airframe weight trends have not varied significantly in recent years, weight growth factors have been decreasing and the overall sensitivity of airplane performance and operating costs versus structural weight have also been decreasing. The reasons for the change in sensitivity are related to technological improvements. These improvements include the use of more efficient materials and construction techniques, greater aerodynamic and propulsion efficiencies, and higher internal packaging densities. Conversely, the structural weight trends (as described in Reference 19) show an insensitivity to higher strength to weight materials and related structural improvements. Apparently, increases in structural efficiency are offset by the imposition of more severe design and operational requirements.

The influence of current structural design concepts and packaging density can be illustrated by reviewing the wing content and structure of a current fighter airplane. The installed wing structure weighs about 1800 pounds. The primary wing bending strength is derived from the upper and lower wing box skins which weight about 735 pounds. A factor of safety change would have the largest impact on the wing skins which comprise about 40% of the total installed wing structural weight. A large percentage of the total wing weight is composed of the flaps, actuators, and seals. These and other miscellaneous components would not be greatly affected by a change in the structural factor of safety.

Recent examples of the factor of safety's influence on airframe weight have resulted from an unofficial Air Force design philosophy for experimental or prototype vehicles. The unofficial philosophy modifies the normal airplane development cycle which includes a series of ground and flight tests to validate airframe integrity. Initial flight tests are normally restricted to 80 percent of certain design maneuver load levels, until ground static tests are completed to ultimate load levels. Flight test airplanes are normally instrumented and critical load points are closely monitored. Flight and ground test loads are then correlated and ground tests are repeated, if necessary, to further validate the structure for the actual flight loads before the airplane is released to fly at 100 percent of design limit load. Such testing is complicated, expensive and time consuming. Although justifiable for an airplane system, when structural efficiency must be optimized, experimental and prototype vehicles cannot be as rigorously tested because of cost and time constraints. To insure equal flight safety at 100 percent of design limit load, without the extensive testing and associated delays, the following procedure has been established:

a. The new experimental/prototype airframe or modifications to existing airframes are designed using a 1.875 factor of safety on loads, which is equivalent to a theoretical margin of safety of +0.25. The initial 80 percent flight restriction normally imposed on an airplane system is also equivalent to a +0.25 margin of safety.

b. The experimental/prototype airframe is stress instrumented at critical design points and proof tested on the ground to 110 percent of design limit load, to insure design/manufacturing integrity. The installed instrumentation is further monitored in flight and compared to the proof load results as a further safety check.

If this design procedure is used, the airplane is allowed to fly at 100 percent of design limit load capability without an ultimate load ground test and without reducing overall safety. Actually, the 1.875 factor and 110 percent proof load test provides a larger ultimate/limit ratio (1.7) than the conventional ratio (1.5). Therefore, testing to 110 percent of limit load is less likely to cause detrimental yielding of the airframe than conventional testing to 100 percent of limit load. For the experimental/prototype vehicle, the philosophy imposes no real penalty because of its "one-of-a-kind" nature and flexible mission status. Two examples of this philosophy will be discussed in the following paragraphs.

The first example is a prototype Mach 2 fighter airplane design which emphasized exceptional maneuverability and typical mission objectives. This prototype design was to be built and used as a technology advancement demonstrator; the design was completed but manufacturing plans were cancelled. The technology objectives have been rechanneled to an existing airplane which will be modified instead. During the design of the proposed demonstrator, a dual airframe comparison was made using the 1.5 and 1.875 factors. The comparison evolved as follows:

a. The design requirement specified the use of a 1.875 factor for flight loads. Computerized design techniques and a highly detailed finite element structural model were used. The available design/analysis flexibility allowed the weight of the airplane and airframe to be established separately for both the 1.5 and 1.875 factors.

b. Two weight comparisons were then established: (1) The airplane gross takeoff weight using the 1.5 factor was 26,465 pounds. Using the 1.875 factor it weighed 27,056 pounds, or an increase of 2.2 percent. (2) The structural weight using the 1.5 factor was 5,095 pounds. For the 1.875 factor, it was 5,433 pounds, or an increase of 6.2 percent. These weights reflect a design service life of 12,000 hours (a service life of 3,000 hours and a scatter factor of 4.0).

The weight growth factor was calculated to be 1.75 (pounds gross weight increase for each pound of structural weight), which is a reasonable value for a fighter airplane.

The second example is the YF-16 prototype airplane. The 1.875 factor was applied to the flight loads and increased the structural weight by 6.6 percent when compared to the 1.5 factor. The weight increase has not been detrimental to its overall performance and would be further minimized if the 1,000 hour design service life of the prototype airplane were increased. The weight increment caused by the larger factor to safety would be partly absorbed by the weight increase required to meet the service life requirements.

Using the same design analogy, a comparison of the weight increase required for different service lives can be seen in another design study of a fighter technology demonstrator of the same weight class. For a 1.875 factor of safety and a scatter factor of 4.0, the airframe delta weight increased about 25 pounds per 1,000 hours of service life. Because of the 1.875 factor, no additional weight was required to achieve the first 1,500 hours. Damage tolerance requirements were not applied during this study but they would have further influenced the airframe weight, increasing it to some degree. Similarly, the 1.875 factor would have lessened the weight sensitivity of the airframe to these requirements.

If, instead of increasing the margin of safety by 25 percent, it were decreased by the same amount, a similar airframe delta weight could be expected for the technology demonstrator. As noted in Figure 5, which is based on the first example, the factor of safety equivalent to the 25 percent margin of safety reduction is 1.125. The use of this "small" factor, when compared to the 1.50 nominal factor, would probably not be considered by a designer even if a large reduction in airframe weight were desired. The airframe weight reduction shown (6.2 percent) may be optimistic because the normal damage tolerance/fatigue life requirements are not incorporated. A 1.25 factor of safety is perhaps a more reasonable value to choose and is shown for comparison. It would provide an approximate 4 percent weight saving and a 16.7 percent reduction in margin of safety. These percentage weight changes and margins of safety are reasonable and reflect current jet fighter design technology trends. Similar data can be found for other airplane types in References 18 and 20.

Reference 18 reflects technology of the 1950's but the trends are still applicable. Data is given for fighter, bomber and transport airplanes and factors of safety between 1.0 and 1.5. The average structural weight saving shown for the three airplane types using a factor of safety of 1.4 would be 2.5 ($\pm$0.25) percent as compared to a 1.5 factor. If a 1.25 factor of safety were compared to a 1.5 factor, the average structural weight saving would be 5.0 ($\pm$0.75) percent. Although these <u>structural</u> weight trends are still current, the range and <u>gross</u> weight trends in Reference 18 do not represent today's airplanes as well. The range increases shown for the lower structural weights assumed a weight growth factor of seven for all three airplane types and additional fuel was substituted for the gross take-off weight "saved." Using these assumptions, jet fighters are shown, for example, to yield a 15 percent range increase and jet bombers a 5 percent range increase or an average of 10 percent for both airplanes. These range increases are based on a gross take-off weight and fuel adjustment that averages 15 ($\pm$3.5) percent when a 1.25 factor of safety is used. These gross weight and fuel adjustments would average 6 ($\pm$1.25) percent when a 1.40 factor of safety is used.

The weight growth factor of seven and the substitution of fuel for gross weight "saved" will give optimistic gross weight decreases and range increases today, since weight growth factors are less. Factors in past years for airplanes have ranged from about five to ten. The weight growth factor for a fighter today would be about two instead of seven and for long range airplanes like bombers and transports a value of five would be appropriate. To illustrate, the trend in Reference 18 for a fighter and a weight growth factor of 7 gives a gross weight savings of 17 percent for a factor of safety of 1.25. The fighter technology demonstrator study gives a gross weight savings of 2.4 percent for a factor of safety of 1.25 and a growth factor of 1.75. For the same factors, Reference 18 gives a gross weight savings of 13 percent for a bomber as compared to 6 percent in Reference 20, which used a growth factor of 5.50. These are only trends, however, and they are debatable, since weight estimating and the establishment of weight growth factors is a sensitive art. To establish accurate values, the factors must be based on a detailed evaluation of a specific airplane and its basic missions.

Reference 20 presents a simplified but constructive parametric study of the factor of safety. Three different vehicle types were selected and designed using a range of ultimate factors of safety. For comparison, three other structural design concepts were included: the modified factor of safety concept defined in Reference 21, Part I; a yield factor of safety concept; and a reliability-based concept.

The conventional factor of safety was applied to the limit design loads of each vehicle in increments between 1.0 and 2.0. The modified factor of safety concept applied a factor of 1.05 to speed. 1.15 to maneuverability and 1.10 to design loads. A yield philosophy applied factors of 1.0 and 1.10 to design limit loads.

The demonstration included cruise, ballistic and glide re-entry type vehicles. Although hypothetical mission profiles and performance figures were used, they were patterned after real vehicles and designed to realistic structural requirements. The structural concepts used were monocoque, semi-monocoque, truss, pressure stabilized and sandwich honeycomb. Two structural concepts were applied to each vehicle, as appropriate to the vehicle type, and radiating and ablative thermal protection systems were applied separately to the re-entry vehicle.

The conventional factor of safety philosophy normally considers only one factor to establish ultimate design loads, without regarding the variables contributing to the limit loads. The yield design philosophy uses a single factor of safety to prevent the design limit stresses from exceeding the material yield stress; an ultimate load factor is not used. The modified factor of safety philosophy also applies a factor to the design limit loads, but these loads are first established by factoring two performance parameters, as previously noted.

A reliability based design philosophy normally considers the statistical distribution and the probability of the combined occurrence of a finite number of structural design factors in order to establish design loads. In Reference 20, the various factor of safety design philosophies were also compared to a structural reliability value. The reliability value was established by considering the statistical distributions and the simultaneous occurrence of two statistically variant design factors.

The parametric study considered both rigid and flexible structure and aerodynamic heating effects when applicable. Weight, weight distribution, and stiffness characteristics were determined for each major component. These parameter variations were correlated to each vehicle's performance and structural reliability.

The scope of the investigation can be considered limited, in that, the structural concepts used were simplified, the analysis methods were not elaborate, and only one critical design point was selected for each vehicle. However, structural weights were optimized, the effects of plasticity were accounted for, and interaction equations were used to account for local and general instabilities caused by combined loading.

The cruise vehicle design is similar to a B-52 bomber in performance, size, weight, and structural flexibility. Gust and maneuver were the critical design conditions. These two-parameters formed the loading interaction curves used to establish an equivalent reliability-based design, as shown in Figure 6. By using available gust and maneuver statistics, the most probable combination of the two design parameters that could cause structural failure at each strength level were located on the interaction envelopes, as shown in Figure 7. Although not an optimum design, considering the complexity of other reliability-based concepts, the most probable failure point is used to illustrate that a lighter structure can be achieved by a reliability-based concept, as compared to a factor of safety concept, even though both provide the same (theoretical) reliability.

The weight reduction for the equally reliable design is achieved by bringing the strength of the individual components closer together. This is similar to using different factors of safety to contour the shape of the interaction curves of overstrength components to fit the shape of the composite failure boundary of the vehicle. This takes advantage of the fact emphasized in Reference 18, that all components do not reach 150 percent of limit load simultaneously. Part of the study results for the cruise vehicle are shown in Figure 8.

The range increases shown in Figure 8 are the result of decreases in the inert (empty) weight of the vehicle. The ratio of inert weight change to structural weight change is about 2.0 and the growth factor between structural weight change and gross take-off weight change is about 5.5. The decrease in inert weight due to the structural weight change, for example, when using a 1.25 factor of safety is about 11 percent, which increases the range 1.6 percent. The dramatic performance increases often seen in such comparisons is not seen here because of the more realistic value of the weight growth factor. The substitution of fuel for either the inert or gross weight saved, although a fuel substitution for inert weight saved is shown, is not considered a realistic design trade. The performance of a specific airplane design is normally optimized using available fuel volume; any additional structural weight saved as a result of a concerted weight reduction program would normally enhance the performance based on the original fuel volume, independently of additional fuel.

Fatigue life and flutter were not design considerations in Reference 20 and their interactions are unknown. Similarly, the probabilities shown in Figure 13 are based only on the interaction of gust and maneuver loads and do not consider other facets such as material properties and workmanship that would also affect the structural reliability.

The gross trends established in Reference 20 should not be significantly affected by the limited scope of the study and the use of simplified structural models. As a general trend, the reliability-based design concept provided a lower structural weight and better performance than did the factor of safety concept having an equal reliability. The modified factor of safety concept gave results closer to the reliability-based concept using two parameters than did the single factor of safety used to obtain the ultimate design loads.

Theoretically, a higher confidence can be placed in a structure designed by a reliability concept than by a factor of safety concept because the actual reliability of the factor of safety design is never known. The reliability-based concept, by contrast, considers the statistical nature of the design parameters and thus acquires a known reliability and the associated confidence level of the statistical data used. In a practical sense, however, this is <u>not</u> true because the design parameters are not well defined and the actual reliability of the structure cannot be authenticated.

The modified factor of safety concept, as incorporated in the comparative factor of safety study in Reference 20, is documented in Reference 21, Part I. The concept was developed as an interium design method to be used until a larger number of parameters could be defined and a formal reliability-based concept established. In Reference 21, forty-one design parameters are described as significant to a reliability-based structural design concept. Fifteen are related to the design environment and operating conditions. The related analysis parameters are: aerodynamic forces, propulsion system forces and pressures, material properties and property variations, thermal stresses, creep of materials, weight and weight distribution, component misalignments, construction, propulsion system thrust misalignments, aero-elasticity and aerothermoelasticity, buffeting, flutter, shock and vibration, workmanship, fatigue, noise, fuel sloshing and surging, structural temperature, ablation, corrosion, oxidation, and erosion.

As a concept, the modified factor of safety can be applied to any vehicle design but it was originally developed for missile design application. The use of three parameters seemed feasible within the current state-of-the-art and the concept is considered to be more "rational" than the ultimate factor of safety concept because it recognizes parameters other than load as significantly affecting structural integrity and reliability. Although the structural reliability of a missile design using the 1.25 factor of safety could not be given a numerical value, the reliability seemed high, and the three factors selected (1.05 on speed, 1.10 on loads or "quality," and 1.15 on maneuverability) were chosen to give a combined strength affect similar to that provided by the 1.25 factor. The 1.05 factor on speed is significant because, for some missiles, small increases in speed result in rapid degradation in structural capacity due to material degradation with rising temperature. Thus, with the initial design based on a higher speed (and hence higher temperature) the designer is forced to avoid the use of materials which are unduly sensitive to temperatures. The 1.10 "quality" factor is applied to the structural loads incurred at specified "maximum" design conditions rather than at conventionally defined "limit" conditions. This concept more rationally accounts for the nonlinearities in aeroelastic and aerodynamic data that frequently occur between limit and ultimate (design) conditions. The 1.15 factor is applied to the maneuver load factor to protect the vehicle from inadvertant maneuver exceedances.

The modified factor of safety concept was used to design the ASSET glide re-entry vehicles. ASSET is an acronym for Aerothermodynamic/elastic Structural Systems Environmental Tests. The ASSET program consisted of designing and flying a series of winged glide re-entry vehicles which were boosted into sub-orbital flight paths. Each vehicle was designed to explore an area of glide re-entry technology that could not be defined in existing ground test facilities. Structural flight test results and data correlations which substantiate the adequacy of the design concept, at least for vehicles having a programmed trajectory, is given in Reference 22.

For an airframe that is not aerodynamically heated, the "load factor" parameter is usually sufficient to convey its overall strength capability. With the introduction of transient stresses and reduced material properties due to thermal gradients, there is no simple method for conveying strength capability (Reference 24). Although a "thermal factor of safety" is not necessarily a "true" factor of safety in the conventional sense, it represents a design concept that is intended to provide an equivalent measure of conservatism and confidence in the heated airframe as that provided by the conventional factor of safety in the cold airframe.

To date, unofficial Air Force policy has been to avoid using any factor on temperature, or heat transfer, or on time at temperature for airplanes. This has been a reasonable policy, since service experience has demonstrated that there is little problem in keeping within a speed-altitude design envelope. Thus, in a sense, the temperatures normally used for design represent the actual maximum to be expected for the structure. This philosophy of not factoring temperature is an apparent contradiction when compared to the philosophy of factoring limit load, which is also considered the maximum to be expected (Reference 16).

The factors of safety used in conventional airframe design to incorporate conservatism also apply to aerodynamically heated airframes, but the conventional factors do not account for the additional uncertainties associated with elevated temperatures. The additional conservatism must relate directly to the uncertainties associated with the prediction of structural temperatures and thermal-structural design analysis. However, the fact that an airframe may have been built to resist aerodynamic heating effects does not necessarily imply an increase in conventional design and manufacturing deficiencies. Initially, the use of relatively unfamiliar materials and forms of construction in the heated airframe and the need for computing structural temperatures with only a limited amount of flight test information, does tend to increase the likelihood of deficiencies. In time, however, these considerations improve and the modification of conventional structural safety factors is not warranted (Reference 23).

As part of an overall Air Force effort to establish a rational design criterion for aerodynamically heated airframes, the velocity factor has evolved as a simple and expedient way of providing and controlling thermal-structural design conservatism throughout the design cycle. The details of this concept are developed in Reference 23. The techniques investigated included factoring structural loads, temperature or heat flux, angle of attack, velocity, and atmospheric density. It concluded that only factors on velocity or structural temperature (or heat flux) are likely to provide an adequate margin when considering the exceedances of performance variables. Of the two choices, the factor on velocity is considered the more logical. The velocity factor provides conservatism in a uniform way at each point in the design mission as a function of Mach Number and the selected size of the velocity factor controls the imposed conservatism.

A thermal factor of safety on loads would introduce an arbitrary (unknown) conservatism; however, a direct, rather than a presumed, margin of safety would exist at the operational level if margins were placed on performance variables instead. Factoring a performance parameter (speed) provides conservatism in a way parallel to that achieved by factoring loads and is preferred to factoring temperature or heat flux since performance margins introduced over operational levels are more evident and controllable.

By requiring a design speed beyond limit, the velocity factor, is in a sense, a factor on heat transfer. However, to specify a direct and specific factor on heat transfer would be a design weakness, in that a number of analytical techniques may exist for a particular area and flight regime, with a large spread in the values they provide. From a structural point of view, the factor of safety should be associated with a particular analytical method. For ablation, varied factors of safety have been used (generally to factor the thickness of the ablator), with different considerations being given to each particular flight application and for applications of the material as an insultator. A factor may also be used to represent a combined factor on heat transfer and on the scatter of the ablative material characteristics. Factors of safety relating to thermal-structural applications can only have meaning when related to the trajectories or flight paths for which they are needed. A factor of safety on a nominal trajectory may be appreciably higher than those corresponding to design trajectories based on a broad parametric investigation or one which places a margin on altitude which represents a factor of safety on temperature (Reference 24).

No single technique can be expected to provide conservatism in a rational way for all contingencies. At best, one type of factor will come closest to providing the desired conservatism and this has been true of the velocity factor. Its use seems reasonable in view of existing factor of safety precedents. A specific design criteria for aerodynamically heated airframes is being formulated and tested by design application. The basic criteria is conventional but it is modified to incorporate the velocity factor concept and attempts to account for many of the design and analysis variables which affect thermal-structural design. The criteria have not been finalized and are based primarily on References 16, 23, and 24, which provide insight to time related load and temperature interactions and the selection of critical thermal-structural design points.

Most of the studies and design concepts reviewed in this Section have evolved as an attempt to further rationalize structural design criteria. As previously noted, these variations to the current factor of safety design concept tend to blend with reliability-based concepts. The next section will discuss certain reliability-based concepts investigated by the Air Force, related design parameters, and data collection programs.

5. RELIABILITY-BASED DESIGN CONCEPTS

The number of publications treating reliability-based design increased appreciably in the early 1950's. Initially, reliability design seemed to imply, at least within the Air Force, the elimination of the factor of safety as a design concept. Statistically defined design parameters and parameter interactions were to be substituted for the discrete parameters and the factor of safety. Too often, however, the magnitude of the problem was overlooked and the acquisition of essential elements were overly simplified.

The Air Force initiated the development of a reliability based structural design criteria for missiles in the mid 1950's. Missiles were one shot devices and unmanned. There was little to lose. Airplanes in turn, were to become mere missile launching platforms that would not require strength for rigorous design maneuvers. Combat was to be conducted remotely. During this swirl of revised committment to systems development, the Air Force established a program to conduct a series of investigations that were to encompass and define the total life cycle of a missile. Considerable priority was given to this effort. The rationalized criteria were to be based on information obtained through data gathering programs and operational experiences. The broad goal was to establish a reliability-based structural design criteria to replace the factor of safety for missiles. This "rationalized" criteria was to be placed in the new structural strength and rigidity specification MIL-M-8856, initially dated 22 June 1959. However, the data base never materialized, the 1.25 factor of safety is still used, and the emphasis to develop a reliability-based criteria for missiles has diminished.

When the need for a reliability-based criteria is considered, a comparison is usually made to existing design requirements and the "need" is often questioned: "Why is a reliability-based criteria required when current requirements and industry practices have produced airplanes having a (seemingly) high reliability?" The answer that evolves must in some way relate to "realism" in design. A reliability-based design concept, as stressed by some in the literature, is inevitable and is the only means of providing greater "realism;" the only way of "rationalizing" the factor of safety concept.

The Air Force first deviated in a significant way from a deterministic design concept by defining probabilistic fatigue design requirements. Although they were applied "deterministically" in the final analysis, the "realism" that operational, environmental, design and manufacturing variations exclude the development of "no-failure" airframes was implicitly emphasized. This is further emphasized by the more recent changes in Air Force philosophy by changing from a "safe life" concept to a "damage tolerant" concept, as described in Section IV.

A related change in design philosophy should also be noted. In 1960, in conjunction with the Navy, the MIL-A-8862 (ASG) Specification, "Landing and Ground Handling Loads," was established and incorporated "design load" requirements. These requirements applied only to the landing loads analysis. Limit and ultimate loads were not specified for these conditions. The incentive to deviate from the 1.5 factor of safety concept was the "realism" provided by available operational statistics of the type described in Reference 17. A general dissatisfaction with the "design load" concept, however, resulted in a change back to the use of a 1.5 factor of safety in the 1971 Air Force revision of the specification which became MIL-A-008862 (USAF). The design load concept for landing loads is still viewed favorably and is being used by the Navy, however.

The Air Force only applied the design landing load concept to two airplanes. On one airplane the concept was applied to the first two models; later models of the airplane were changed and redesigned using the 1.5 factor of safety. Unfortunately, the limited application of the design landing load concept also limits the experience base available for evaluation. Apparently, there was very little, if any, penalty involved between the models which employed the two concepts. The infrequent application of the design load concept and its eventual elimination from MIL-A-8862 can be traced to: (1) an Air Force requirement that transport airplanes be compatible with and certified to FAA requirements; (2) a lack of clarity in the specifications and differences of opinion regarding which "loads" are affected by the design load concept and which ones are not (carry through structure, nacelle attachments, external tank and store attachments, etc.); (3) difficulties in the interpretation of interactions with other requirements relating to material yielding and aeroelastic effects; and (4) the added difficulty of applying static test loads to the airframe through the lower strength landing gear. The overriding reason for these implementation problems, however, appear to be poor planning. The concept was conceived and implemented too quickly and without appropriate trial applications. No loss in design efficiency is expected (with respect to static strength requirements) by using the 1.5 factor of safety, however, because current durability, damage tolerance, and dynamic taxie requirements will add more weight than could be saved by using either the design load concept or the factor of safety concept.

The Air Force maintains structural design specifications and handbooks to preserve past experiences, correct previous mistakes and prevent design oversights. This effort attempts to maximize structural integrity and reliability, but the concept is not foolproof. New mistakes are always possible with the rapidly changing state of the art and the increasing severity of the operational environment. Because of these complexities, the documents are difficult to keep current and new or revised design requirements are normally written into the statement- of-work for any new system development, if they occur between the revision intervals of a specification. Criticism, then, that certain specifications are not current or that certain requirements are not rational, may be correct but they do not hinder new system developments. When similar criticisms are leveled at the 1.5 factor of safety, however, the evaluation is not so simple; should it be replaced with a reliability-based concept? What is generally not appreciated is that the basic airplane design loads (static strength) are essentially statistical in nature. The design values are derived from a broad spectrum of operational experiences. If a distribution were assumed, then the design limit and design ultimate loads would represent a certain probability of occurrence and exceedance (Figure 9). A justifiable criticism of the factor of safety, though, is that a fixed factor does not recognize the variation of load or strength and does not provide a uniformly efficient structure (Ref 25). This effect was illustrated in References 18 and 20, as discussed in Section IV.

Unofficial Air Force recognition of a variable factor of safety concept has been established by allowing certain structural design deviations. The static test failure of an engine inlet duct at 1.3 times the limit pressure, for example, was accepted when it was established that the internal dynamic pressure in the duct would not exceed the design pressure in a dive. The resultant delay, re-design and cost to bring the duct structure up to the normal strength level of 1.5 times limit pressure was therefore avoided (Reference 25).

The Air Force has not formally adopted a reliability-based structural design criteria, although some requirements have an associated probability of occurrence. Available procedures that could be adopted vary in concept and detail, but their philosophical principles are the same. References 26 and 27 summarize some of the philosophical aspects that appear in the open literature and also note the complexity of the reliability-based design problem, as paraphrased in the following two paragraphs.

The many proposals for a more rational criteria are related to the appearance of new structural materials which exhibit improved strength and stiffness or weight characteristics. Other considerations are the extreme increases in the structural loading environment and concern with economic costs. Designing to an acceptable risk while keeping all design factors in proper economic perspective would seem to be effective but the concept of risk must be quantified before an acceptable risk level can be determined. The new materials also tend to exhibit variations which could, in a deterministic design, require such large factors of safety as to nullify the improvements. The increase in extremes of the structural load environment are primarily new to the civil engineering field while economic costs are perhaps new to the aeronautical field. [Reference 28 notes that the aeronautical engineer has for many years considered new failure criteria (fatigue and creep), new materials and construction (brittle materials; fiberous weaves) and more complex loading conditions (temperature-load histories); this has resulted in greater variability in the applied and failing loads than has been encountered in the past.] Picking the worst possible load conditions for design is no longer considered economically feasible under a broad spectrum of load conditions and the statistics of extremes must be considered for rational design. Reliability-based analysis permits a more consistent approach to structural safety by including the statistical variability of load and strength in the factor of safety evaluation (Reference 26).

Most of the early studies in probabilistic design considered only the fundamental problem in which all of the strength variables and the load variables were lumped into two random variables. These studies concentrated on the effects of different safety factors, coefficients of variation and frequency distributions. Later studies included multi-member and multi-load structures, different levels of failure and the application of decision theory. Several problems must be considered in the context of a reliability-based design. First is the reliability analysis of structures with derived or assumed probability distributions for random variables, including load and strength distributions; developing and constructing the necessary computational models which account for indeterminancy, the types of failure modes (including elastic, brittle and collapse modes), the number of load conditions and failure modes, and their statistical correlation. Another problem is the design of a structure in the context of a random variable of safety for a given probability of failure; the random variable could be cost or weight. An additional problem is that of parameter sensitivity and determining their affects in the load and strength descriptions. Most reliability analyses assume that strength and load distributions are known; the high cost of obtaining load and strength data will probably necessitate the acceptance of lower confidence levels in structural design than professional statisticians usually recommend. Subjective statistical analysis is needed together with studies to determine the effect on optimum weight and cost due to changes in choice of frequency distribution, coefficients of variation and other parameters (Reference 27).

As part of its program to maintain and develop structural design criteria, the Air Force has sponsored various investigations intended to lead to a reliability-based criteria for both airplanes and missiles. One investigation (Reference 21) was partially presented in Section IV. This investigation will be further discussed with two others (Reference 29 and 30). These three investigations emphasized static strength reliability, although fatigue or durability requirements can be incorporated within these concepts. Other Air Force investigations have more thoroughly emphasized the fatigue aspects of a reliability-based criteria. Reference 31, for example, treats fatigue design considerations while Reference 32 emphasizes fatigue but also provides limited treatment of static design considerations. Reference 31 is an extension of Reference 32 and Reference 33 is an evaluation of the concepts in Reference 31. These fatigue related references are noted here only for completeness and will not be emphasized further. The three investigations relating primarily to static strength design considerations, however, will be summerized in more detail because of their direct correlation with the factor of safety concept. In expanding these three reliability-based efforts, the philosophy of the techniques will be emphasized and not the technical aspects of their development or application.

A statistically based concept developed for missile design is found in Reference 21, Part II. The concept is broad, however, and can be applied to almost any reliability-based design problem. The design concept is basically a "framework" developed to be consistent with the premise that there is no definite demarcation between safe and unsafe design, but a gradual change in reliability between safe and unsafe. The idea that a sharp change exists between safe and unsafe can cause unnecessary redesign for every slight change in design load or reduction in allowables. Redesign should be required only when the over-all reliability of the system decreases appreciably. The term "framework" applies because the wide scope and complexity of the problem did not allow final refinements to be made. This concept, as discussed in Reference 21, is described in the following paragraphs.

This concept uses any number of design variables that are essentially independent of each other to determine interaction envelopes that separate failure from non-failure regions. Design parameters are presented so that "criticalness" continuously increases as parameter values increase or decrease. By superposition, a single interaction envelope is formed and the probability of not generating points in the failure region is the quantitative reliability of the system for the time period considered. To simplify the computation of reliability (which could be obtained by integrating the content), an equivalent value of each parameter is defined such that the envelope content is approximated by simple multiplication of the probabilities associated with the probability value of each parameter. Any number of statistical parameters can be used. Limits are imposed only by the analysis time and data available. As data is defined, the number of parameters can be optimized and should include five to eight that are random varying and fifteen to thirty that are systematically varying; any distribution can be accomodated without the necessity of having to find a special function of the variable.

The intersections of any two interaction curves are defined as "nodal points," which are used as design points (Figure 10). The analysis is relatively insensitive to the exact interaction envelope shape because any reasonable envelope shape having the same content will pass near the same design points. The design conditions or nodal points are defined by two parameters, one having a "limiting value" ($X_{L.V.}$) and the other a "reference value" ($X_{R.V.}$). The probability value ($X_{P.V.}$) at each point is equal to the limiting value minus a correction factor ($X_{C.F.}$) which is approximated by analyzing representative probability distribution shapes of significant parameters (Figure 11). The pictorial representation is limited but a mathematical extension is completely valid and feasible for any number of parameters.

Power spectral techniques are used to evaluate time dependent effects, and other simplified techniques were developed for handling systematic variations. A method for determining the required confidence levels of parameters is also given to assure consistent reliability analysis, and accommodations are made for fatigue and creep effects. Greater approximations are allowed for secondary design effects than for primary effects.

The basic concept, then is a semi-empirical method for quantitatively determining the reliability of a defined structure, or for the design of a structure to a prescribed reliability. The development is based on and justifies two basic premises: (1) that by the judicious selection of design (nodal) points the true interaction envelope shape is unimportant and (2) that the reliability of a system can be calculated with sufficient accuracy by simple multiplication of the probabilites of equivalent parameter probability values rather than by integration of the interaction envelope content. Although seemingly complex when reviewed, the method of Reference 21, Part II, can by using a minimum of parameters and certain refinements, and with some additional development and appropriate data, approach the factor of safety method in simplicity.

A different reliability-based concept is found in Reference 29. Reference 21 developed a statistically based quantitative structural design criteria that relates the probabilistic nature of design, operational and environmental experiences to structural performance. Reference 29 developes a deterministic structural design criteria that uses a quantitative objective and statistical techniques, as described in the following paragraphs.

This design method is characterized by the thought that the ability to calculate a probability of failure when load and strength spectra are <u>assumed</u> to be known, are quite different than the ability to determine the <u>true</u> structural reliability of an operational structural system. The method also incorporates certain considerations that appear to be overlooked in other approaches. These "oversights" are: (1) errors or discrepancies which occur between actual and calculated spectra; (2) the influencial effect of testing as a means of design error disclosure; (3) the necessity for demonstrating proof of compliance with requirements; and (4) the necessity for assigning responsibility for actions which affect structural reliability. Other interactions with non-structural, operational, managerial and contractural areas are also included. The overall investigation and proposed design concept evolved in three steps.

The first step evaluated the various functions which contribute to structural design. The second step evaluated and compared the current factor of safety concept and a (hypothetical) purely statistical structural reliability concept to the structural performance and design functions established in the first step. The third step evaluated existing and proposed reliability-based concepts to the same standards of evaluation used in step two. These evaluations concluded that: (1) the current factor of safety design technique is a satisfactory system but that more stringent future requirements will minimize the effectiveness of the system; (2) a purely statistical structural reliability-based system is not practical since there is no way to accurately measure structural reliability and it is not possible to write definitive requirements to demonstrate the reliability (proof of compliance); and (3) that none of the known structural reliability-based concepts in the literature today provides a satisfactory foundation for a quantitative structural design criteria based on statistical methods. To elaborate slightly and provide an appreciation for the design concept which evolved, the philosophies which governed the development will be expanded in the following paragraphs.

The fundamental purpose of any structural design effort is to develope an operational structural system that satisfactorily performs its mission. This development is the result of many management and engineering decisions which are a key element in the success or failure of the design effort. One aspect of the factor of safety concept is that the design effort can be practical and easily administered because it has an inherent proof of compliance (test) provision. Its fundamental problem is that it has no clearly identifiable quantitative design objective to satisfy. The available logic cannot resolve the comparative adequacy of different factor of safety values. In some design areas, such as, fatigue or high temperatures, the factor of safety is not even directly applicable to the definition of the design requirements. The concept only defines a relationship between limit and ultimate load, which normally controls the design strength level and does not allow for an assessment of its "correctness," other than "failure." Positive margins of safety do not prevent failure; gross errors in design loads, analysis and large strength scatters contribute to failure at limit load or less. Structural tests, on the other hand, are a nearly perfect disclosure of gross errors if the strength scatter is small, as is customary. The trend toward greater scatter and a lessening or inability to disclose analytical errors, requires that the possibility of failures below limit be considered more seriously in the future. Further, test conditions are normally selected on the basis of the strength analysis, and the actual design conditions are becoming more difficult to simulate when testing; successful ground tests, therefore, do not guarantee successful operational performance, and flight testing will remain an important design development consideration regardless of the design concept used.

Current requirements have evolved primarily as a reaction to past problems and the assumption that future structural systems will have the same characteristics as past systems is not necessarily valid. When structural failures do occur, the deterministic nature of the factor of safety concept allows the determination of the cause, the responsibility, and the corrective action to be taken. Unfortunately, because of the many interactions between the structure and other design areas which contribute to structural integrity, responsibility is not always recognized until after a failure has occurred. These and other considerations previously noted relate primarily to the factor of safety concept, but they also interact with reliability-based concepts. Especially important are the considerations that establish design compliance and responsibility when failure occurrs. When cause and responsibility are not determinable, neither is the corrective action.

The structural design concept that evolved in Reference 29 utilized the desirable features of the factor of safety concept and improved or replaced those not desirable. The following basic characteristics are included in the concept:

1. The deterministic type of requirements that give the factor of safety concept its praticality and administrability are retained.

2. A clearly identifiable objective that serves as a basis for judging any proposed modification to the factor of safety concept is established.

3. A structural reliability goal is part of the objective. The goal is not a requirement since structural reliability, per se, cannot be determined accurately enough to serve as a contractual requirement.

4. The techniques to convert the structural reliability goal into deterministic requirements based on statistical considerations are developed.

5. The capability to deal with structural systems having large strength scatters is incorporated.

6. Specific problems such as fatigue and high temperature design can be integrated into the structural design to attain the defined objective.

7. The crucial interfaces with non-structural design requirements are identified. Provisions are made for assigning responsibility for every function that affects structural integrity.

8. The concept of testing as a disclosure of error in formulating design requirements is utilized.

Basically, the structure should have a capability to survive designated overload and understrength situations caused by undetected errors or oversights. The factor of safety concept provides this capability but the provision is indirectly and inconsistently applied. Structures with large strength scatters are basically more prone to fail from understrength considerations rather than from overloading. The concept in Reference 29 establishes separate and distinct requirements for understrength and overload situations. The requirements are based on probabilities and statistics and are selected to be consistent with a level of structural reliability appropriate to the airplanes mission. The design and mission relationships are illustrated in Figure 12. The central bar indicates that the limit design load includes a provision to handle an understrength structure to avoid failure at limit load. The right or left bar indicates the overload provision. The left bar illustrates a large overload provision and overrides the understrength provision. This could represent a relatively low reliability, high load factor fighter airplane. The right bar illustrates a design situation with a smaller overload requirement. The understrength provision is now more critical and governs the design. This could represent a design requirement for a highly reliable, low load factor transport airplane. Once the appropriate design values are chosen, they become deterministic and are as easy to administer as the conventional factor of safety concept.

The first implementing step is to select a structural reliability goal consistent with the mission. The goal is not a requirement and suggested values are given in References 29 and 30. The limit and ultimate design conditions are two separate conditions based on the reliability goal and established by statistical or qualitative considerations, which reflect available experience. The design limit condition is the upper bound of a normal or expected (permissible) operating condition while the ultimate condition is an abnormal operational condition reached only as the result of an operational error or failure of a non-structural system. Failures within the understrength design provision are a structural responsibility and require correction, while failures from overloads require operational corrections. There is no fixed factor of safety separating the limit and ultimate condition; the ultimate condition in Reference 29 does not represent the conventional meaning of ultimate load. The condition is separate and unrelated to the limit condition, whose meaning does not change. The "ultimate" condition is a "design" condition based on a rare or abnormal situation and may be significantly different from the conventional ultimate load.

The basic structural design is qualified and approved by conventional ground and flight tests. Ground test loads are defined by a limit or an ultimate test factor of safety. The factor selected varies according to the established structural reliability goal and by the number of tests conducted. Example values are shown in Figures 13 and 14. Flight tests are conducted in a conventional manner and operational flight load monitoring are required to verify operational consistency with design. If not consistent, the structure would require modification when operations are detrimental or the operational procedures may require some change.

There are many ramifications, qualifications, advantages and disadvantages related to reliability-based design concepts as expressed in Reference 29. Most of the associated disadvantages or problems are not new but have always been problems, such as the statistical definition of design data. No new problems are created by introducing reliability-based concepts but old problems became more clearly defined. The basic advantage of the proposed concept in Reference 29 is its ability to establish structural performance in terms of a quantitatively definable goal. This permits the definition of the minimum structural requirements to meet the goal. It also permits the justification of a less severe structural design criteria when warranted. Because each of the design aspects is quantitized, trade-offs can be made between criteria reductions and the difficulty (technical, cost, time) of providing more efficient structural characteristics.

The proposed reliability-based concept in Reference 29 is reviewed in Reference 30 to identify data requirements, necessary changes to design specifications and handbooks, interactions with non-structural design areas and the steps required to implement the concept. To illustrate each step of the concept, Reference 30 uses a simple design example. First, simplified dummy data is employed and then realistic data. The categories of required data are defined further by a study of data pertinent to the C-141 cargo airplane and then by a trial application of the concept to its wing. The revision of data to reflect an improved state-of-knowledge at each design stage and during the life of the vehicle, and the form in which the required data might be standardized, is also discussed. Although the limited study did not allow an extensive treatment of data requirements, Reference 30 provides insight to the complexities of the data problem as it relates to reliability-based design and similar concepts. The data requirements, limitations and design interactions are presented in the following paragraphs.

To be effective, data must be established and updated continuously. Fundamental data are operational load spectra, error functions and strength distributions. These data will change periodically during the total lifetime of a specific airplane. The particular periods that permit progressive updating are the initial, detail and final design phase, before and after tests, and before and during airplane operations. It is the operational environment that provides the best opportunity to obtain quantities of new data, which are also pertinent to other design concepts.

In June 1954, a special panel report (Reference 34) of the NACA Subcommittee on Aircraft Loads recommended a program to obtain statistical information on maneuvers and related inflight loads, whether caused by pilot inducement or atmospheric turbulence. The panel also recommended that the Air Force and Navy obtain time histories of three linear and three angular accelerations about mutually perpendicular axis, airspeed and altitude to establish a statistical design base. The recommended statistical maneuver load program was initiated as a joint effort by the Air Force, Navy and the NASA in 1956.

In 1958 the Air Force outlined a long term program to collect and utilize flight measured data. The program, initiated in 1959, was to develope techniques for integrating the statistical data into existing design criteria, review and improve the data recording and reduction, and to establish fundamental requirements for structural criteria based on statistical methods. The resulting effort identified certain problems which were grouped into three categories: the definition of design conditions, the definition of component strength distributions, and mathematical procedures relating the first two to structural reliability. The program also led to the sizing and establishment of a data reduction facility by the Navy and an 8-channel recorder development program by the Air Force. State-of-the-art limitations eventually terminated the recorder development program and in turn closed the data reduction facility in 1969. References 35 and 36 are documents relating to this effort. Other investigations which have defined data requirements and collection programs for missiles are described in References 16, 24, 37, 38, 39, 40 and 41.

More recently, the operational data recording program for airplanes has continued as the Air Force's Aircraft Structural Integrity Program (ASIP), as defined in Military Standard 1530A, by the same title, dated 11 December 1975. As part of the ASIP, each airplane system will be monitored to obtain time history records. The parameters necessary to monitor operational usage and derive stress spectra for critical structural areas will be measured in approximately 20 percent of the operational force.

To accomplish the ASIP, the Air Force initiated plans in 1968 to develop a new and more universal multi-channel recording system, to less stringent standards than the previous 8-channel recorder. New requirements were prepared and in June 1970 the development of a 24-channel digital recording system and a ground playback unit were started. The system has been developed and is now in limited use. The data tapes for each system will be collected and compiled at a single location when the program is fully implemented. The parameters measured and sample rates can be varied to the specific needs of each system. Plans to establish the necessary parameter correlations and design load spectra from the ASIP data are being formulated.

The major objective and justification for the multi-channel program is to provide a better tool to accomplish fatigue tracking. However, because of the high commonality between data needed for fatigue and statistically based strength design, the reliability-based design concepts will also benefit. When a recorder program on a certain system "matures" to the point that statistical stability is obtained and no new operational fatigue related information is produced, or when certain parameters attain statistical stability and need not be recorded full time, the resulting surplus of recorder capacity can be used to establish statistical strength criteria or to fill knowledge gaps; for example, the phasing of Power Spectral Density (PSD) loads. In gust analysis, current PSD methods allow a fairly precise, but separate, determination of shear, bending and torsion at a given location; the phasing of the three vectors is largely a guess. The addition of strain gage clusters or rosettes at selected locations could provide actual examples of the amplitude and frequency relationships. Such data will be essential in future designs to express applied loads and structural strength in a common set of terms.

Ideally, derived data can be standardized and categorized. A convenient approach would be provided by charts relating the required design and test factors to the reliability levels in terms of parameters describing the load strength distributions, the error function and the number and type of tests. Theoretically, it would appear possible to develop a single load spectrum for each location, which would contain the total load occurrences for an airplane lifetime. However, the simultaneous consideration of both limit (normal) and ultimate (abnormal) loading conditions will seldom be possible because the permissible strength level will generally be different. Each structural location will require separate analysis, since both load and strength distribution will differ from point to point.

The statistics available, even on airplanes which have extensive operational experience, are not adequate. For example, additional information is required on the probabilites of: (1) weight and weight distribution; (2) speed and altitude; (3) types of load conditions (gust, pull-up, rudder kick, etc.); (4) level of loading (in terms of a basic parameter); (5) time history of loading (to describe local loading); (6) associated load systems (pressure, thermal gradient, etc.). These probabilities are not independent and the resultant probability of each combination is also needed. In addition to the average or typical conditions defining each segment of the mission profile, it is necessary to derive or assume the shape and distribution about the mean. Without this detailed level of data, no realistic estimate of the risk of failure can be made.

Although extensive material strength data exist, the allowables represent only one discrete point in the distribution. The form of data required consists of the mean and standard deviation and the shape of the distribution to be used. The structural strength of the final component will also reflect the variations imposed by all of the inherent operations in fabrication and assembly. Data on the strength of various structural configurations exists only in a random manner and usually in insufficient quantity to provide adequate statistical distributions.

It is frequently necessary to assume that all observations are of a single homogeneous population whose distribution follows a standard form. Such assumptions often give good fits near the most frequently occurring values but for the structural reliability problem other factors require emphasis. The major difference between structural and common reliability analysis is that the "mean time to failure" is not a desirable measure of reliability. It is the risk of failure that is required for a structure. There is no "acceptable" failure rate and much more emphasis is therefore placed on high (abnormal) loads and unusually low strengths. This emphasis, then, requires that the statistical representations match the appropriate tails of the distributions rather than the region near the more frequently occurring values.

The formal recognition of possible errors is probably more important than the specific definition of an error function. The error function may describe any number of discrepancies, however caused, in terms of the distribution of the probable mean strength of the structure. A number of suitable functions are available for initial design use. The degree of dispersion (coefficient of variation) has relatively little influence once the test results have been incorporated, when tests are used as an error disclosure. A relatively low risk would probably be introduced by the adoption of a standard error function.

The implementation of any reliability-based technique will present certain problems and Reference 30 suggests a two stage process. Initially, there will be insufficient data available to implement a total reliability-based design concept and emphasis should be placed on the comparative similarities with the existing factor of safety design concept rather than the differences. However, even restricting the reliability concept to design conditions for which data is available will help establish a correct understanding of the probabilistic processes and encourage the acquisition of the data required for further implementation.

The first phase would apply the reliability concept to selected design conditions and primarily emphasize familiarity with terminology and mathematical relationships; the relative importance of parameters; evaluating the implied reliabilities of existing airplanes; and insuring that continuity with existing design concepts exists so that no abrupt changes in structural integrity will exist. The interactions between "static" strength, "fail-safe" strength, "fatigue" strength and "damage tolerance" strength also require identification to permit the whole spectrum of structural reliability to be expressed in a consistent manner.

The second or final stage, that of achieving a meaningful, completely probabilistic concept will not be possible until quantities of additional statistical data are obtained, especially for asymmetric flight cases and combinations of parameters which are not independent. Not only must every possible cause of loading be established in probabilistic terms, but every factor affecting the strength must be established. Unless a total picture is assembled, nothing will be known about the relative importance of the various design conditions and interactions, or about ways of changing the reliability results by modifying the operating conditions or by redesign of the structure. When reliability results are further specified as a single numerical value, even when specified as a goal, the relative merit of different values regarding safety and possible redesign must be considered. The concept of a single numerical value for the reliability of an airframe or even a specific location on the airframe is superficially attractive, but any real advantage is completely offset by problems of interpretation of the number. Any judgement as to acceptability of one reliability number over another that is slightly different will remain arbitrary. It is probable that a relative risk assessment technique will prove to be worthwhile even when all of the necessary statistical data are available and a completely probabilistic design concept can be achieved. Final implementation will be governed by experiences gained during the first phase and the availability of design data.

The next section will attempt to place these thoughts and ideas, and those of previous sections, into perspective by further relating them to current design practice.

6. CONCEPT INTERACTIONS

The factor of safety has lost some of its appeal in recent years and probability analysis has been emphasized as a more "rational" concept. Formerly, the complexity of reliability-based concepts centered around the analytical aspects of the solutions but this difficulty has been off-set by current computer technology. Today the prime restraint is available design data in the proper statistical form (Reference 21).

Dissatisfaction with the factor of safety concept became more apparent during the early 1960's when surveys of airplane and missile manufacturers were conducted in conjunction with various Air Force structural design criteria development programs. The general industry feeling that the factor of safety is growing more and more inadequate has apparently not changed. The initial dissatisfaction applied primarily to missiles, but airplanes were not excluded. The surveys also found that the degree of availability of flight measured data varies greatly between systems. Its quality and quantity are both deficient and the parameters most needed for reliability-based design concepts are often not measured. Cost and the inability to access a system for the purposes of instrumentation and data measurement often become insurmountable problems.

Whether using a factor of safety or a reliability based concept, the airframe's probability of failure will be sensitive to the number of significant design parameters (assuming all significant parameters are accounted for) and their statistical distribution. The design data must encompass all of the natural environments, induced environments, operational variations, materials properties, and built-up structural properties; the total number of specific parameters requiring statistical definition becomes significantly large. The state-of-the-art and practical limitations in establishing accurate statistical data for each significant parameter is such that the actual results may be more academic than related to actual needs. Unless the available data are carefully selected and reduced, considerable effort could be expended with few commensurate results.

Although the validity of extrapolating data for design use is taken for granted, certain precautions must be exercised. Too often design data have been compiled from inappropriate or limited samples. Data must reflect operational conditions from all segments of the Air Force; pilots must be "qualified" or "typical," not highly experienced flight test pilots; weather conditions must be proportioned between good and bad flying conditions, and daylight and night operations; and weather cycles occurring during the year and over a period of years must be considered. Some parameters have physical limits or "practical" upper limits and any assumed ditribution must consider a reasonable cut-off value. Extreme values become less accurate as they progress away from the mean and influence design confidence. Values selected closer to the mean could affect flight safety. As a "logical" extension of the realization that all airplanes of a certain type cannot (statistically) meet the design "economic" or fatigue life expectancy, there is a trend to develop exceedance curves for design that represent "average" rather than "extreme" environments. Formerly, airplanes were always designed to the maximum expected or extreme environments for both static and fatigue strength and the static loads induced were increased by the factor of safety. The affect of this design trend on flight safety cannot be assessed, but the importance of selecting proper design parameters and having a factual data base increases.

The limitations which inhibit induced load measurements have led some to believe that the factor of safety should be retained on loads, but that all other design considerations (which are assumed to be well-defined) should be evaluated by a rational statistical analysis. These concepts might lead to a refinement of current design procedures, but it does not change them since statistical considerations have long been a part of airplane and missile design criteria. Although probability factors for structural design are seldom expressed in current criteria, the choice of limit load factors for static and fatigue strength and various environmental design parameters are fundamentally based on flight and environmental statistics (Reference 24).

Perhaps the most important contribution to airframe safety is that of testing. As so aptly noted in Reference 42, "safety regulations, however good and sophisticated, should always provide for approval based upon relevant experiment, such as the measurement or control of actual loads, the measurement of the actual strength of components, and the demonstration of the performance of the complete structure by proof or stiffness tests." This practice has long been the custom of the aeronautical engineer. Both ground and flight tests are used to demonstrate design integrity and optimize the conflicting requirements of minimum weight and maximum structural reliability. Optimization and economic airframe life requirements have in recent years placed considerable emphasis on developmental testing. This emphasis will probably increase in future years. Although testing is a very cost effective design and substantiation "tool," the expense of testing is a major obstacle to obtaining more appropriate statistical data for reliability-based design concepts and statistical substantiation of structural reliability. Some of the interacting roles of structural analysis and testing are discussed in Reference 43.

A natural extension to current practice is the use of additional factors and design parameters. This concept is less complex and easier to manage in a rapidly changing design environment than using a variable factor of safety. The modified factor of safety concept (Reference 21) factors three performance variables and it could be expanded to include others. Going further, Reference 38 suggested that the factor of safety on loads for missiles could be reduced in certain instances when a particular load source is highly predictable, thrust for example. However, Reference 16 expressed the view that although some design load sources are highly predictable, the combined design load may be exceeded for some design conditions when components of the combined load are reduced. In effect, known conservatisms compensate for the unknown.

The additional design complexity imposed by a new or revised concept on structural analysis must be considered, too. Associating a specific factor with a specific variable, regardless of the number of factored variables, will provide a certain level of additional complexity to a load/stress analysis; using a variable factor of safety and specific parameters will add a different level of complexity. Computerized analysis techniques can relieve some of the bookkeeping, but considerable additional judgement in design is required as compared to using a single factor of safety on load. Although less complex, the single factor of safety on loads will not satisfy the objective to control structural reliability; the single factor is a function of numerous variables which can vary structural reliability appreciably and not impose a change on the factor itself. Also, if new factors of safety are applied to additional design parameters or if revised or variable factors are applied to loads, the years of experience and back log of compensating design limitations and related requirements which we have for the conventional factor of safety will be lacking and design confidence will decrease until a new base can be established.

Major changes in airframe design technology are usually accompanied by a comparison with existing techniques prior to adoption. Reference 30 illustrates a limited comparison of this type as discussed in Section V. Other studies have made comparisons relating "equivalent" factors of safety to a "compatible" reliability. Such comparisons can be found in References 28, 44, 45, and 46. There is a similarity between reliability and factor of safety concepts which becomes more obvious when the factor of safety is viewed as a concept based on the statistical definitions of many basic design parameters. Each design parameter, however, is normally reduced to a specific value and the concept becomes deterministic rather than probabilistic. To further the analogy, the design (ultimate) and operational (limit) stresses can each be assumed linear and represented by a frequency distribution. The ratio of the mean stresses of each assumed distribution can then be defined as a factor of safety. Reference 44 uses this analogy to show that the level of reliability can vary widely for the same factor of safety value. As proportional changes are made to the stress ratio or to the shape of the distributions, the overlap of the tails of the distributions varies and, in turn, the reliability varies. A fixed factor of safety cannot, therefore, ensure a constant level of reliability without considering the statistics of the design strength and operational stresses. Reference 44 further explains that the factor of safety can be placed on a more rational basis and, in fact, only has meaning when related to the concept of reliability.

The degree of safety desired or required also varies according to the particular point in the V-G diagram which is involved. The left hand corners of the diagram represent maximum lift coefficient and the maximum load possible (not considering the small increase in maximum lift coefficients that can occur under dynamic conditions and which may be used in constructing the diagram), and thus, if a static test has been conducted satisfactorily and validated by flight measured loads, it would be physically "impossible" to have a static structural failure at these points when operating normally. A similar statement may be made of the flight controls, which are limited in loading to specific boost capacities, and in a more general sense, to inlets which are designed to specified pressures corresponding to maximum speeds to which the airplane will fly. The airplane may physically exceed the design speed (and maneuver limits), but it has turned out in practice that pilots have kept within speed (and maneuver) limits without difficulty. In these cases, it might be logical to consider a lower factor of safety than that considered for the right hand corners of the V-n diagram (Reference 25).

Exceptions to normally controlled flight conditions are instabilities which cause design load factors to be exceeded. The factor of safety does not recognize aerodynamic instabilities in design. Even with an extensive operational background, past experiences show that all static flight failures cannot be predicted. Several "modern" airplanes have been lost because of unaccounted for aeroelastic affects. Some losses were the result of aerodynamic interactions and one resulted from improperly predicted span wise wing loads. Some structural failures could have been prevented within the state-of-the-art but others have resulted from new phenomena not anticipated or as a subsequent event to a prior turbulence upset (Reference 25).

More recent examples of structural failure can be cited for both fighter and transport airplanes. These examples resulted from control system malfunctions. Gross in-flight structural failures subsequently occurred to the wings of the airplanes. Spars were cracked and major thick-skin wing planks became detached, but the instabilities were eventually overcome and the crews survived. If these structures had been designed to a lower factor of safety, or to a "design" load (rather than limit/ultimate) concept having an effective factor of safety lower than 1.5, these airplanes would probably have failed catastrophically in flight. This failure projection is hypothetical, but these real examples of structural overload reflect the inherent conservatism in today's airframe and the need for overload protection. It is unlikely that the dollar value associated with the cost of the airplane and crew training, for any one of the several airplanes affected, could be off-set by the "savings" in weight, the performance "gained," or operational costs "saved" by using a design concept that might provide a lower level of structural safety.

There is another measure of safety to be accounted for beyond the "normal" over-load/under-strength probability limits of structural failure. Extraneous causes of structural failure may arise which are not part of an original design evaluation. Instances of poor maintenance, improper assembly or reassembly, substitution of improperly heat treated components, etc., are well know. Other phenomena such as hydrogen embrittlement and stress corrosion may not be adaptable to statistical design procedures and the statistical limitations of small coupon or structural component tests are also well know. Even if these events can be statistically accounted for, their significance could overshadow the probability of "normal" structural failure when considering reliability-based criteria (Ref 25).

There is still another safety aspect to consider. The factor of safety does interact with other design and analysis requirements, although it is often viewed as an independent measure of structural safety. Reference 47 is a study of comparisons between existing and proposed Civil Engineering requirements that emphasize a similar interaction. The study first notes the many uncertainties in design and construction that are covered by providing "overload" protection. The facets noted are identical in context to those considered within the factor of safety concept for airframe design. Similarly, the factor of safety concept is noted to be a crude method of covering analytical and construction errors, but the reference also notes that it has the merit of simplicity. The study itself evaluated a variety of structures exposed to three loading conditions. It compared the quantities of flexural steel required for each design case and assessed the theoretical "overload" capacities of the structures. The steel requirements using both the old and new requirements were found to be very similar for each loading condition, but the presumed overload protection was found to vary. It was initially presumed and implied in the specifications that the theoretical overload protection would be proportional to the factor of safety associated with each load system. However, the strength was not proportional to the factors of safety used. This occurred because the design of the adjacent spans in the structure used different factors depending on whether they were loaded or not; in some cases, the loaded spans were couterbalanced by an exaggerated (factored) dead load on the adjacent unloaded spans. The overload capacity of the loaded spans, then, was not directly proportional to the factor of safety.

Even though the study showed a variation in overload capacity, existing structures designed to these requirements were still considered safe for several reasons; occurrences of actual overload were negligible, the probability of understrength was low, and "inevitable detailing" excesses (design conservatism) existed. One additional reason, however, is most important and relates to the elastic analysis. Until recently, the complexity of the elastic analysis encouraged the use of simplified assumptions which required up to 70 percent more steel than would have been required by a more rigorous analysis. The additional material, in turn, greatly increased the overload capacity of the structure and led Reference 47 to conclude with this question: "With the increasing use of computers, which make more rigorous analysis, --- will structures designed according to --- (existing requirements) --- or similar types of load system(s) still be adequately safe?" This question is equally applicable to the 1.5 factor of safety design concept for airplanes.

The following are similar points emphasized in Reference 29. The main point emphasized is that the conventional factor of safety provides for (unknown) situations that might <u>not</u> be recognized in a more sophisticated ("rational") design procedure. Any attempt to be too sophisticated can also lead to design procedures that are impractical. To avoid these possible problems, new and old concepts should be closely compared. Any large differences in the results should be viewed with caution and not be accepted uncritically. It is further noted that different results, either more or less critical, are not necessarily adverse and can often be justified under appropriate circumstances.

The concluding question in Reference 47 should also be expanded to reliability-based concepts: If more complex reliability-based design concepts are eventually implemented to "rationalize" existing requirements, "save" airframe weight and "improve" performance, will the "new" structures still be adequately safe? There is no immediate answer available. Hopefully, any change in design concept will bring with it an adequate and equivalent level of airframe safety; however, any design concept is a balance of requirements involving numerous parameters and design interactions and any new concept for which experience is limited must be thoroughly evaluated and closely monitored to ascertain the true affect of the change on structural safety.

Generally, reliability-based concepts are not proposed to improve flight safety. Flight safety is always a concern and new design concepts are generally not adopted until an equivalent or better level of safety is assured. The most significant reason normally given for adopting a new concept is to achieve a reduction in weight when compared to the accepted norm. This reason is well intended but could also be misleading. The accepted norm can be elusive and difficult to define and the projected "savings" in structural weight can be easily overstated. Every design concept attempts to maximize efficiency and avoid either an unconservative or an overweight structure. In this respect, current design practice has been very effective. Reference 19 provides some insight to the history of structural efficiency for bomber and transport airplanes up to 1964. The observation is that airplane weight trends and structural weight fractions are very consistent. It makes no difference whether an airplane is jet powered or propeller driven, whether it was built 25 years ago or is of recent (1964) vintage. There remains a balance between an efficient structure and/or material and the design requirements imposed on them. Studies of future airplanes (beyond 1964) also supported this trend (which still seems valid today). It is apparent that if more efficient materials and types of construction are found, that more stringent operational requirements will be imposed on them. Time and state-of-the-art advances seemingly have little affect on basic structural weight trends. Reference 19 describes the weight trend curves as basic, and as such, a technological break-through would be required to significantly change them.

The trends, of course, are based on the conventional factor of safety design and metallic materials; any improvement in structural weight trends that might result from the use of a reliability-based design concept or from composite materials when used on an actual airplane is unknown. These concepts may provide the necessary break-through. However, an airplane design is the result of many compromises and interactions which have a neutralizing influence on overall design with respect to any one parameter. Too often weight and performance improvements are estimated superficially and the optimistic conclusions are not achievable. A thorough study that incorporates the major performance and airframe parameter interactions in a design evaluation is required to obtain a confident weight impact assessment and many design variations would be required to establish a new trend. The pacing influence on performance improvements to date have come from advances in propulsion concepts, not structural concepts. Structural designs have successfully kept pace, however, and structural efficiency has improved. But as pointed out in Reference 19, when greater structural efficiency is achieved, greater demands are made and the structural weight fraction has not changed appreciably.

The actual impact of design data, analysis, weight and test interactions on the development and application of future reliability-based concepts cannot be clearly defined at this time. The similarities between the factor of safety and probabilistic techniques indicate that any state-of-the-art improvements intended to benefit the implementation of a probabilistic concept would also benefit and improve the factor of safety concept. This is especially evident when considering a design data base and may be an additional point to consider when evaluating changes in current design concepts.

There appears to be a slightly subdued, but continuing interest within the aerospace industry to develop a design concept that improves the "deficiencies" associated with the factor of safety concept. It has been assumed that any lack of clarity in the merit, goals or direction that might be associated with a reliability-based concept, will be resolved satisfactorily as the concept is implemented.

The remaining section will briefly summarize the salient traits of the concepts reviewed and project a possible balance in their future application.

7. SUMMARY

To have emphasized only structural design concepts with respect to flight safety is in keeping with the intended scope of this review, but emphasizing too limited a view could be misleading and detract from other important safety aspects. Safety considerations in a broader view are discussed in References 48 and 49 and serve as a reminder of the overall scope of the safety problem. Safety is a total operational system and all aspects must be considered in unison.

The static strength safety aspects of the airframe have been "controlled" primarily by the 1.5 factor of safety. To be more precise, the factor of safety has been the most visible design aspect of airframe safety and it serves as a unit of measure in that regard. It provides protection to occupants from both understrength airframes and inadvertent overloads. But the overall concept of safety must again be emphasized and not just the factor of safety; the factor does not function alone but in concert with many other structural design and operational requirements.

The 1.5 factor of safety in U.S. design practice is fundamental, and represents a level of design safety which has become an accepted standard. Although the concept is accepted and used without reservation, it has remained in an intermittent state of review. Its efficiency as a design concept has been challenged and the objectives of its design application cannot be clearly identified. There are proponents who have encouraged change and proponents for the status quo. To define the arguments and differences between them is sometimes difficult.

Perhaps the 1.5 factor of safety is "rational" and does not require revision. Or perhaps the 1.5 factor of safety is "arbitrary" and its basic function cannot be defined sufficiently to establish a revised value. Its history seems to say that the 1.5 factor of safety is a mixture of both elements. The 1.5 factor is "rational" because it is based on what were considered to be representative ratios of design to operating maneuver load factors experienced during the 1920s and 1930s (which have not appreciably changed today) and it is "arbitrary" because we still do not know the exact design, manufacturing and operating unknowns and variations it protects against, or how to quantify them. Neither can the degree of inflight safety provided by the 1.5 factor be quantified, but its successful history cannot be lightly dismissed.

Reliability and realism seem to go together. Probabilistic design concepts are considered more realistic and have been proposed as being more rational than the factor of safety. Reliability-based concepts have, therefore, been proposed to replace the factor of safety concept. Because of anticipated implementation delays, interim design techniques have been proposed and consist of multiple factors of safety which are related to specific design parameters and variable factors of safety which are related to specific design needs.

The primary justification and final objective of the probabilistic concept is to improve airplane performance and reduce operating costs. These improvements are to be gained through reduced airframe weight. However, recent airplane weight studies and past weight trends have shown that the actual airplane weight saved is often less than anticipated. Durability, fatigue life, and damage tolerance requirements also influence airframe weight and tend to supersede savings gained through "improved" design techniques. These requirements add weight beyond that needed for static strength.

There are many design and operational (and possibly legal) ramifications to be defined before the factor of safety concept can be formally changed with assured justification. The lack of appropriate statistical data, the need for procedures to establish the true structural reliability of a design and to demonstrate (verify) contractual requirements will also hinder implementation of a reliability-based design concept.

Reliability-based concepts are difficult to define and understand in summary form because of their complexity, but regardless of the advantages or disadvantages alluded to herein, the concepts cannot be lightly discarded. They must be examined critically and objectively, simultaneously defining the needed design parameters. Yet, a completely rigorous reliability-based concept may be so impractical for structural design that it may be less desirable than the easily administered (less rigorous) factor of safety concept. In time, the application of reliability-based concepts to airframe design will increase, but the degree of their application may have a definite limit. Future concepts will probably evolve to incorporate both a simplification of the purely statistical reliability-based concept and the gross simplicity of the factor of safety concept. The factor of safety still covers many contingencies and at this time it appears there will be a need for some factor, and to a greater degree than is sometimes implied (References 21 and 25).

The objective has not been to support or minimize a particular structural design concept but to underscore certain points seldom emphasized. All of the disadvantages noted apply to both the factor of safety and reliability-based concepts. The point is, that the reliability-based concept will not eliminate all of the "problems" of the factor of safety concept or necessarily offer a "safer" design. In fact, the "problems" may tend to increase because of limited design experience with statistical concepts and the use of statistically "defined" parameters that may be of questionable validity. Furthermore, there may be an unjustified confidence in computed reliability estimates, although reliability-based design concepts have been assumed to be more rational than factor of safety concepts. The physical results of a reliability-based design and the related statistical data must be more than a mathematical nicety; the statistical confidence expressed in the design must be realizable, in fact. Finally, regardless of the design concept adopted for future use, the safety of the airframe will depend not only on that concept, but on the adequacy of the total structural design criteria and the ability of the concept to meet the proof of compliance requirements of the design specifications (Reference 25).

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SS-5 - "Specification for Determination of the Equivalent Semi-Wing and the Structural Mean Chord from the Properties of the Actual Wing."

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Name	LOAD FACTOR FOR				LOAD (Lb/Sq. Ft.)	
	High Incident	Low Incident	Inverted Flight	Landing Conditions	Ailerons and Horizontal Tail Surfaces	Vertical Tail Surfaces
Pursuit	12.0	6.5	4.0	7	35	30
Observation	8.5	5.5	3.5	6	30	25
Light Bomber	5.5	3.5	2.5	5	25	20
Heavy Bomber	4.5	3.0	2.5	5	20	15
Primary Training	8.0	5.5	3.5	7	35	30
Advance Training	8.0	5.5	3.5	7	35	30
Cargo	5.5	3.5	2.5	5	25	20

Figure 1. Design Loads for Major Assemblies (Reference 1)

ANC - 1 (1)	SPANWISE AIR LOAD DISTRIBUTION - NAVY
ANC - 1 (2)	CHORDWISE AIR LOAD DISTRIBUTION - NAVY
ANC - 1 (3)	DETERMINATION OF POINTS OF APPLICATION OF RESULTANT AIR LOADS - NAVY
ANC - 1 (4)	RELATION BETWEEN AERODYNAMIC AND INERTIA LOADS - NAVY
ANC - 2	GROUND LOADS - ARMY
ANC - 3	WATER LOADS - NAVY AND BUREAU OF AIR COMMERCE
ANC - 4	METHODS OF STRUCTURAL ANALYSIS - BUREAU OF AIR COMMERCE
ANC - 5	STRENGTH OF AIRCRAFT ELEMENTS - BUREAU OF AIR COMMERCE
ANC - 6	METHODS OF STRUCTURAL TESTING - ARMY
ANC - 7	DETAIL DESIGN - ARMY
ANC - 8	PROPELLERS AND ENGINE ACCESSORIES - ARMY
ANC - 10	PERFORMANCE CALCULATIONS - NAVY
ANC - 11	PERFORMANCE TESTING - ARMY
ANC - 12	VIBRATION AND FLUTTER PREVENTION HANDBOOK (DECIDED UPON IN 1938 EXECUTIVE MEETING) - CIVIL AERONAUTICS AUTHORITY

Figure 2. Army Navy Commerce (ANC) Committee Programs and Publications (Reference 2c)

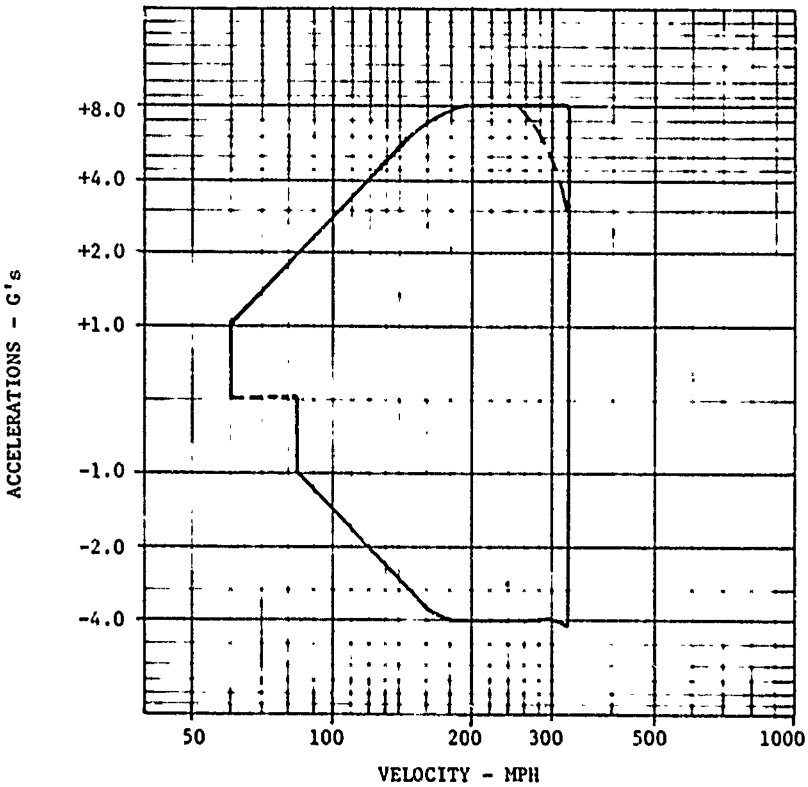

Figure 3. Navy V-G Diagram, Log-Log Coordinates and Rounded Corners (Reference 2c)

STRESS ANALYSIS CRITERIA

- BASIC FLIGHT CRITERIA
- WINGS AND WING BRACING
- ALIGHTING GEAR
- CONTROL SURFACES, INCLUDING FIXED SURFACES, AND AUXILIARY DEVICES
- CONTROL SYSTEMS
- ENGINE MOUNTS AND NACELLES
- FUSELAGE AND HULL
- FITTINGS

Figure 4. Specification X-1803 Classifications (Reference 2c)

STRUCTURAL FACTORS OF SAFETY	STRUCTURAL DELTA WEIGHT	ULTIMATE MARGINS OF SAFETY
1.125	-6.2%	-0.250
1.250	-4.0%	-0.167
1.500	0.0	0.000
1.750	+4.0%	+0.167
1.875	+6.2%	+0.250

Figure 5. Structural Weight and Margin of Safety Variations with Changes in Factor of Safety

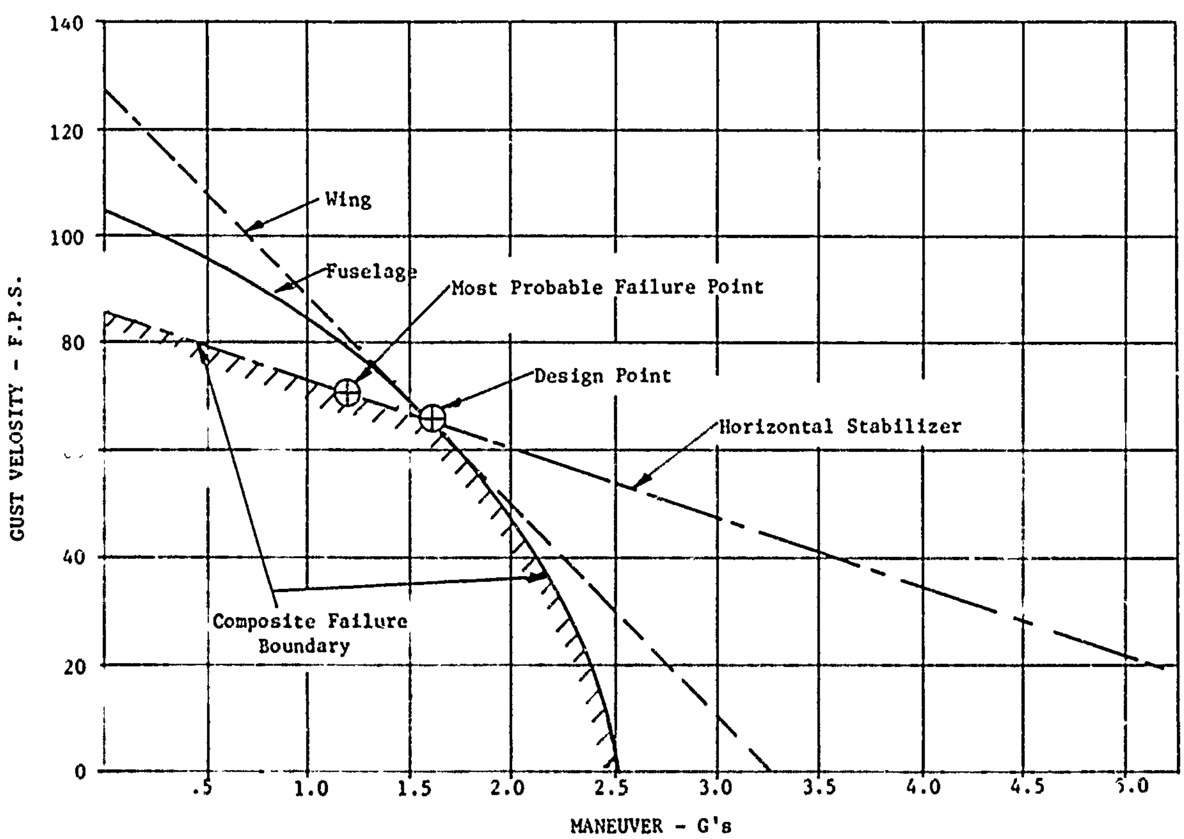

Figure 6. Example of Interaction Envelope Construction (Reference 20)

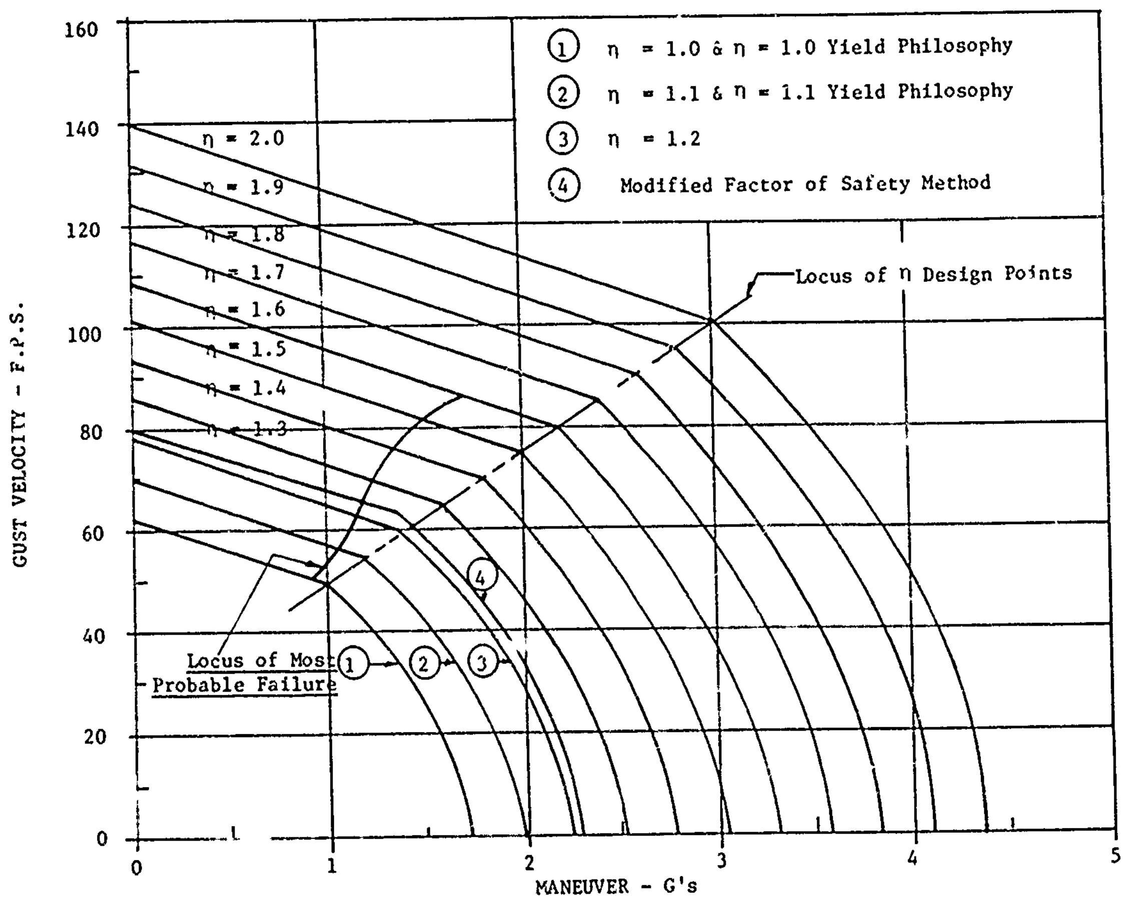

Figure 7. Structural Limitations Large Cruise Vehicle (Reference 20)

Structural Design Concept		Weight Change			Wing Root Stiffness		Range Increase	
Factor/Eq Rel.	Reliability	Structure(1.0)	Inert(2.0)	Gross(5.5)	Bending	Torsion	Inert Wt	w/Fuel
1.50 Factor	$10^{-21.5}$	1.000	1.000	1.000	1.00	1.00	1.000	1.000
Eq Rel (1.5)	$10^{-21.5}$	.984	.968	.980	.87	.94	1.004	1.009
1.40 Factor	10^{-14}	.979	.958	.977	.93	.97	1.006	1.013
Eq Rel (1.4)	10^{-14}	.962	.924	.958	.81	.92	1.011	1.021
1.30 Factor	$10^{-8.3}$	.957	.913	.953	.87	.94	1.012	1.024
Eq Rel (1.3)	$10^{-8.3}$	.943	.886	.937	.76	.90	1.016	1.030
1.25 Factor	$10^{-6.2}$	.945	.889	.940	.83	.93	1.016	1.030
Eq Rel (1.25)	$10^{-6.2}$	.938	.876	.932	.74	.90	1.017	1.032

Figure 8. A Comparison of Weight and Performance Changes with Different Factor of Safety and Reliability Concepts for a Large Cruise Vehicle (Reference 20)

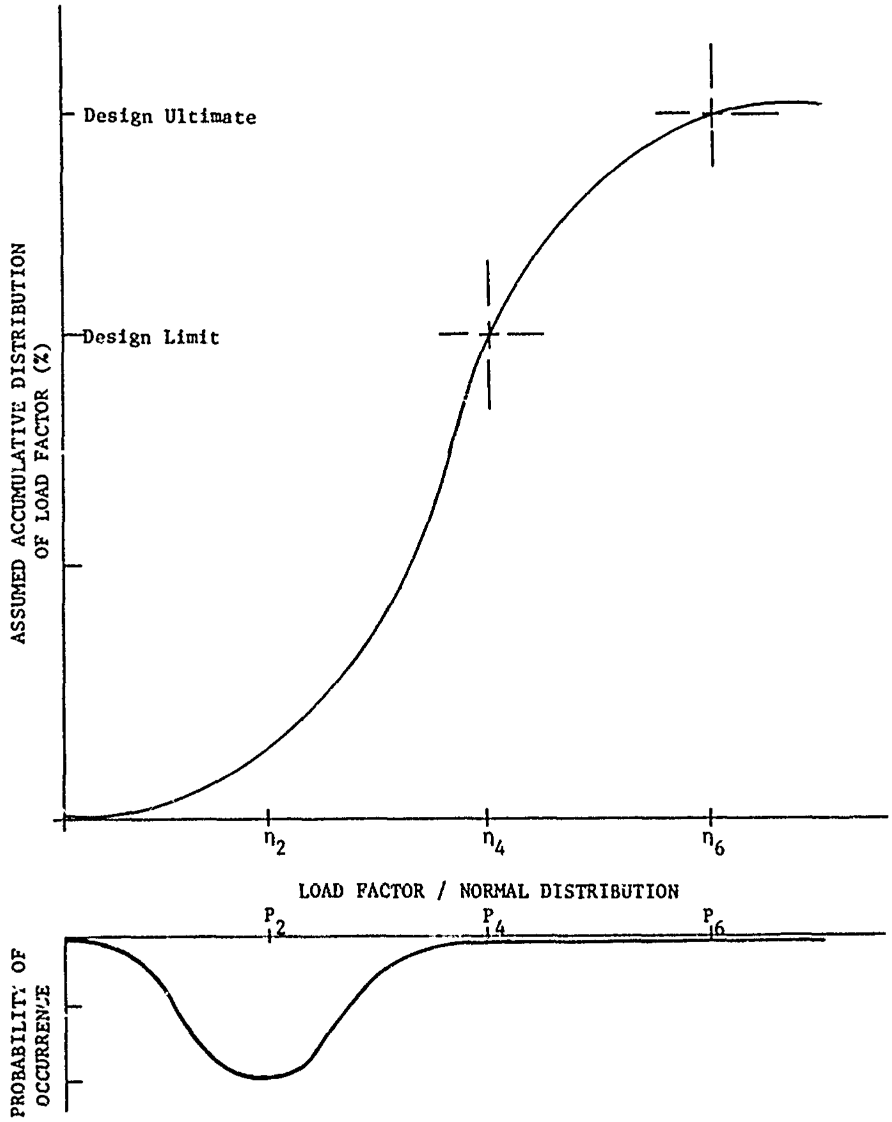

Figure 9. Statistical Representation of the Factor of Safety Design Concept

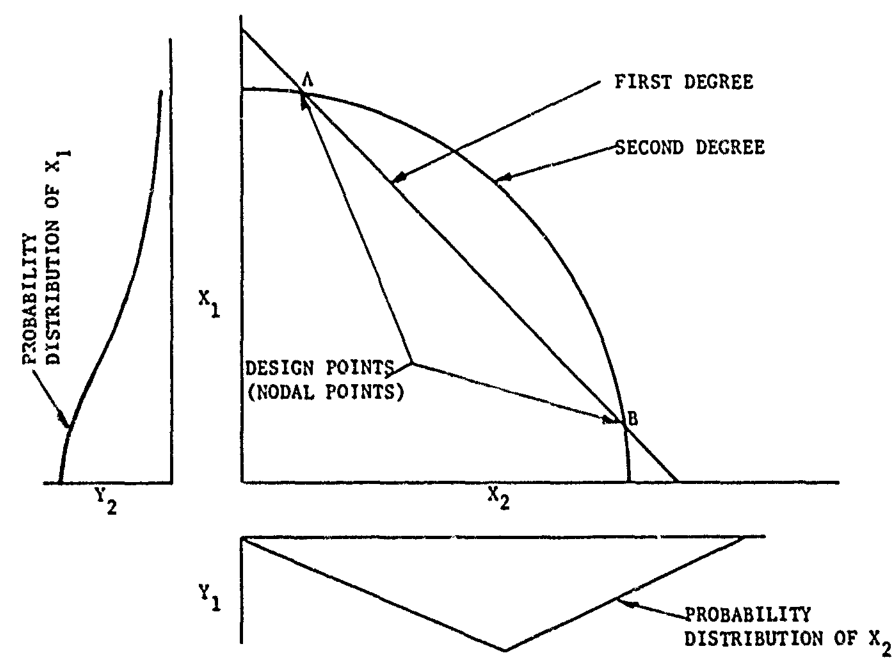

Figure 10. Two Parameter Probability Distributions and Interaction Envelope (Reference 21)

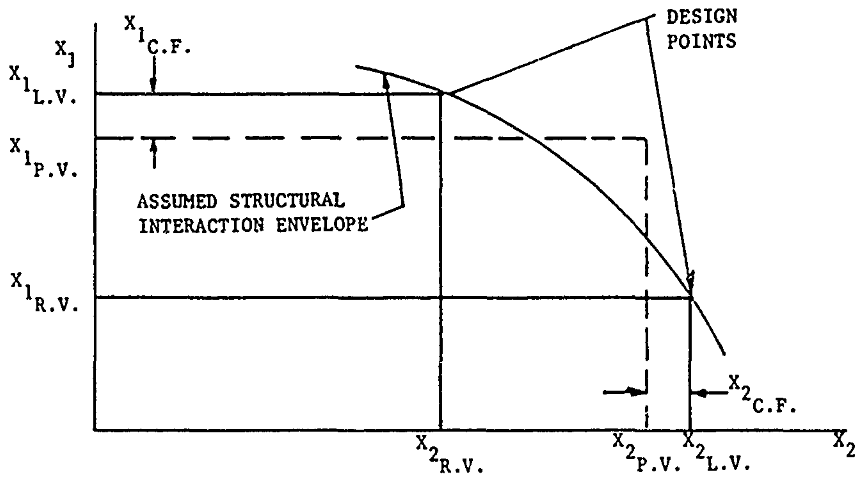

Figure 11. Location of Design Points (Reference 21)

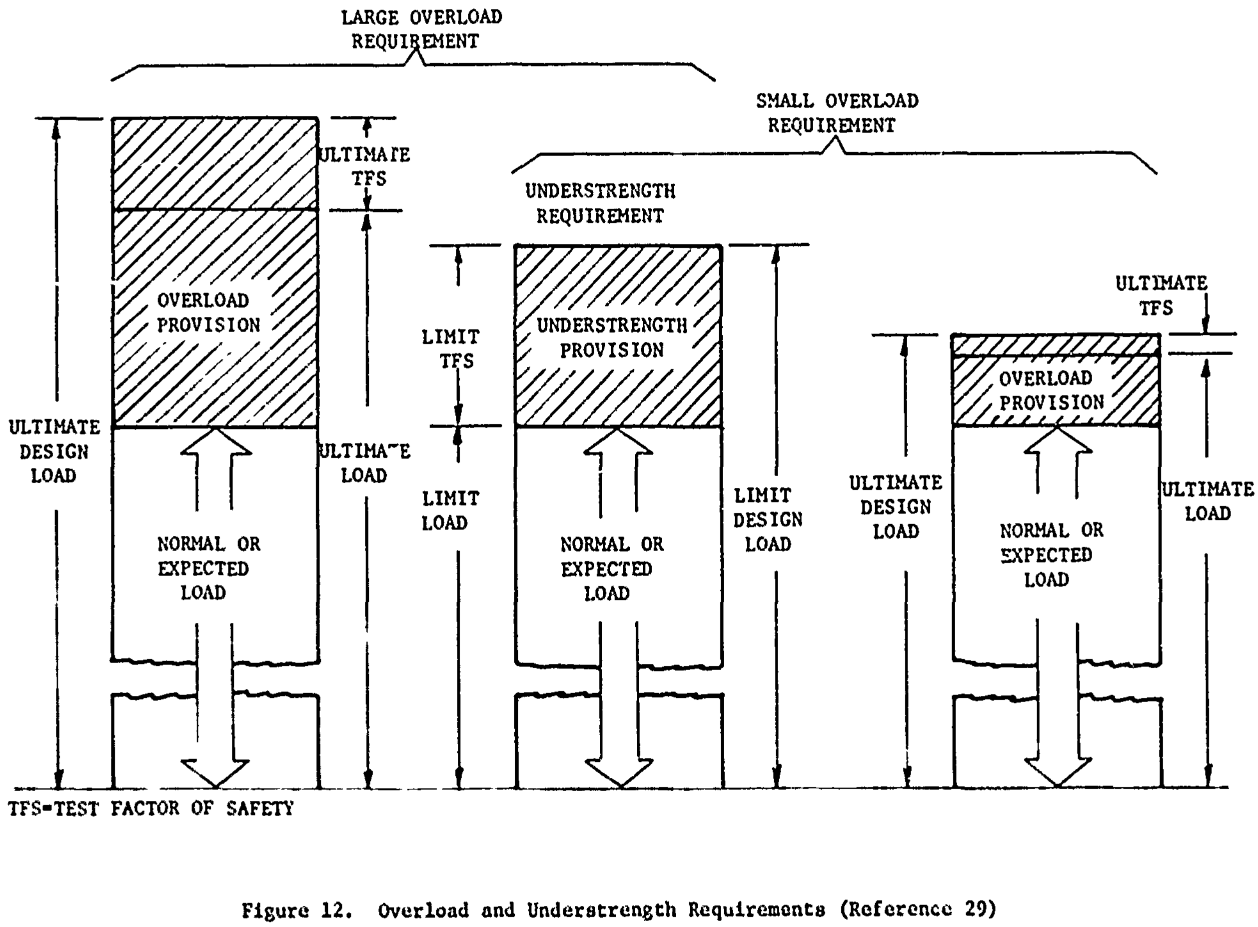

Figure 12. Overload and Understrength Requirements (Reference 29)

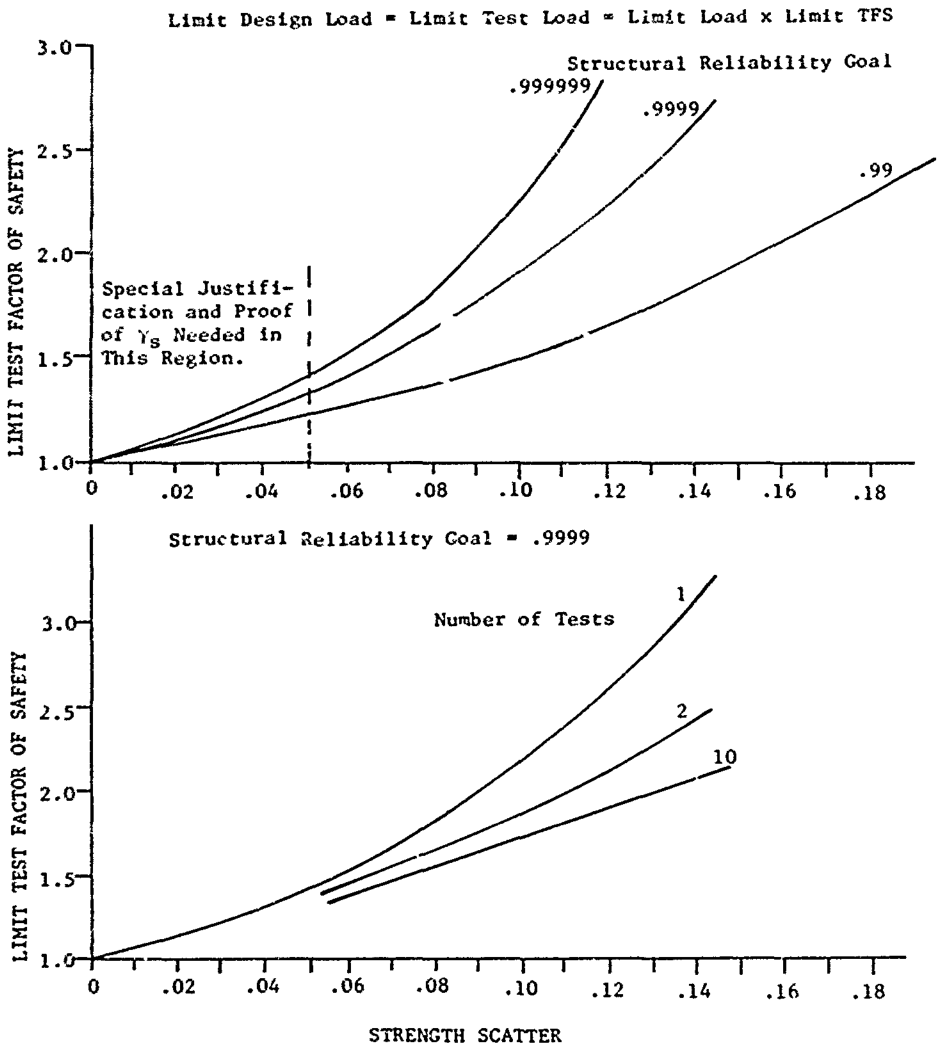

Figure 13. Limit Design and Test Factor of Safety for a Given Structural Reliability Goal Versus Strength Scatter (Reference 29)

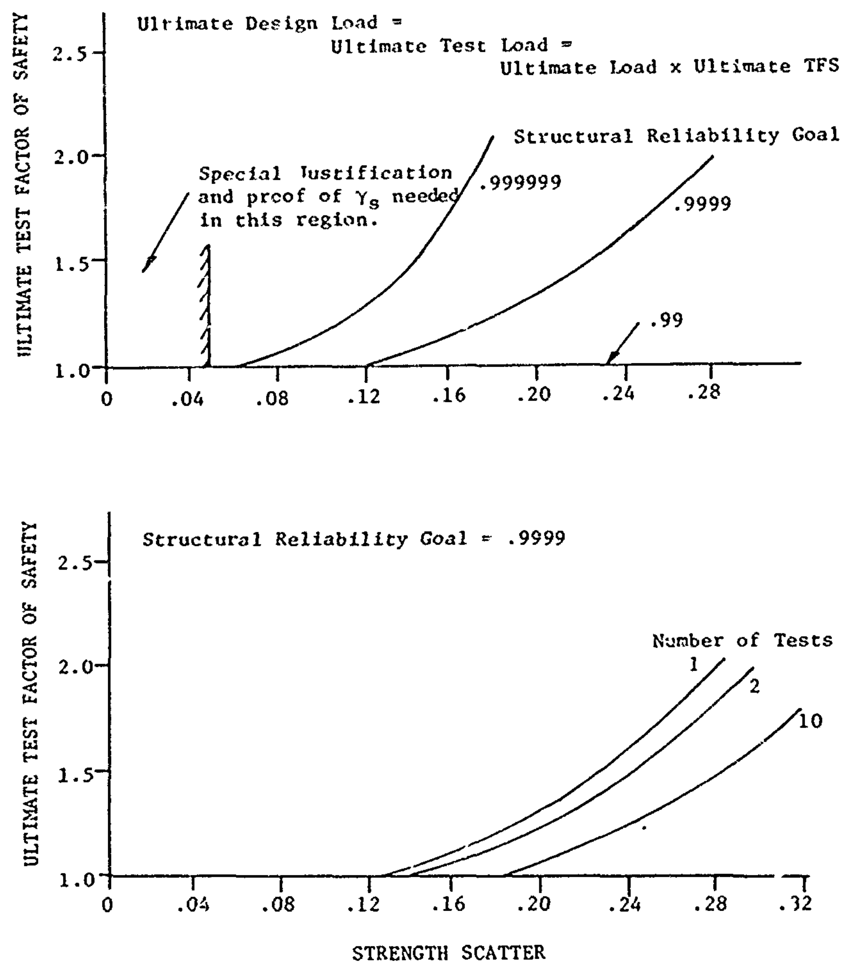

Figure 14. Ultimate Design and Test Factor of Safety for a Given Structural Reliability Goal Versus Strength Scatter (Reference 29)

THE LABORATORIO NACIONAL DE ENGENHARIA CIVIL AND THE STRUCTURAL SAFETY CONCEPTS IN CIVIL ENGINEERING

by

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Lisbon, Portugal

1. INTRODUCTION

This opening presentation is divided into two completely different subjects.

First a brief description of the Laboratório Nacional de Engenharia Civil (Portuguese Civil Engineering Laboratory) LNEC.

Thereafter a summary of the present situation concerning structural safety concepts in Civil Engineering.

The description of LNEC is justified by the fact that the AGARD meeting is taking place in its campus.

The presentation of structural safety concepts is justified by the possible mutual benefits that can derive from a comparison of structural safety concepts used in Aeronautics and Civil Engineering.

2. THE PORTUGUESE CIVIL ENGINEERING LABORATORY, LNEC

The Laboratório Nacional de Engenharia Civil, LNEC, is a research institute in the domain of construction related to Civil Engineering. It gives technical support to the activity in the following fields: building and town planning (housing, schools, social equipment), transportation (roads, railways, harbours and airports), power production (hydro electric, thermic and nuclear plants, overhead electric lines), industrial and agricultural buildings, building materials, elements and components; design and construction.

It depends on the minister of Public Works direct, and is in close contact with the remaining state departments, and public and private enterprises concerned with the above fields. As it also carries out specialization and professional up-grading activities, it keeps in touch with institutions mainly devoted to education.

LNEC, with its staff of about 1,000, of which more than two hundred are graduated people, may be considered an important research institution not only on national level but also by international standards.

Perseverance in training, improving and selecting its staff for about thirty years has made it possible to assemble a group of researchers, specialists, assistants and other technicians and administrative personnel who form a valuable patrimony. In the near future there is the purpose of enlarging the specialized technical staff in such a way as to increase LNEC capacity to meet Portugal's needs for research and to continue collaborating in the resolution of problems put by foreign organizations.

LNEC is organized into 8 departments and 38 technical or administrative divisions.

The total operation cost of LNEC in 1977 amounted to about 300 million escudos, of which about one third corresponds to state appropriation, one third is granted from investment plans to research and one third corresponds to contracted studies and services.

The LNEC campus is about 22 hectares. Its total floor area is about 70,000 m^2.

To give support to research activities, LNEC has a computing centre, which is also used by a large number of public and private organizations on a time-sharing basis.

It also has some design offices and workshops for developing mechanical and electronic test equipment not available on the market. Some of that equipment has been patented, and is commercialized by LNEC mainly abroad.

To back up research, LNEC is provided with a library which contains about 100,000 publications and receives more than 800 periodicals. The library carding index contains above 600,000 entries. Automation of bibliographic research is already a fact for some domains (roads, hydraulics), and it will progressively be extended to further domains.

Research is conducted following four-years plans that obey guide-lines set for longer times, and are put to effect by means of yearly plans. Four research plans are in progress: a government's investment plan that gives support to building research, a plan for housing studies, a plan for hydraulic studies, and a plan for studies on roads, railways and airfields, all provided with their own funds. All such planning is carried out in coordination with bodies concerned with activities in these fields. The total number of studies included in these plans amounts to about two hundred.

Research applied to resolution of specific problems related to design and construction of civil engineering works is made on contract. Planning and budgeting precede every study. As studies progress the control of their execution and cost is carried out.

In addition to research, LNEC carries out a large number of other activities, such as: standard tests, drafting of specifications, standards and codes, delivering of agreements and classification of building materials and components, control of materials production, observation of structural behaviour, general information and advice.

Particular reference should be made to specialization and professional upgrading activities under the form of seminars, courses and technical information sessions.

The seminars are mainly meant for updating and discussing knowledge on specialized subjects. They disseminate research activities and contribute towards the training of LNEC specialists as well as other technicians particularly of holders of study grants working at LNEC. The training of specialists is extended to non-LNEC trainees who by completing a study programme and submitting a thesis can qualify as research officers and principal research officers.

Professional upgrading courses, held in Lisbon and in several other towns in Portugal, are meant for the professional upgrading of technicians concerned with the building industry.

Technical information sessions have the purpose of divulging recent achievements in different domains.

The dissemination of knowledge is backed up by the publication of numerous documents: technical papers, technical information sheets, manuals, text-books, specifications and booklets of several kinds.

A general assessment of its action since it was created in 1947 makes it clear that the LNEC has succeeded in achieving the goals that were set to it. In addition to contributing towards progress of knowledge in several domains, it has solved a large number of problems put to it either by national or foreign organizations, and moreoever it has conducted many other actions for the benefit of the Portuguese technology with the aim of contributing to the social and economic progress of the country.

3. STRUCTURAL SAFETY CONCEPTS IN CIVIL ENGINEERING

3.1 The Activity of the Joint-Committee on Structural Safety

The improvement and implementation of structural safety concepts is the basic aim of the Joint-Committee created in 1971 and sponsored by the following international associations in Civil Engineering: CEB – Euro-International Committee for Concrete, CECM – European Convention for Constructional Steelwork, CIB – International Council for Building Research Studies and Documentation, FIP – International Federation for Prestressing, IABSE – International Association for Bridge and Structural Engineering, and RILEM – International Union of Testing and Research Laboratories for Materials and Structures.

Several international bodies such as: ECE – Economic Commission for Europe of the United Nations Economic and Social Council, CEE (Common-Market) Commission of European Communities and ISO – International Organization for Standardization are working in the harmonization of international rules for the design and execution of structures for different types of construction and material. This harmonization implies unification of basic concepts.

The improvement and unification of basic concepts are upstream of the harmonization of specific rules. Consequently the terms of reference of the Joint-Committee are of great importance.

An extended unification of concepts and design rules should allow mankind to benefit from existing knowledge collected through international cooperative work. However, the fixing of concepts hinders progress. This duality has been considered and steps have been taken to try to maximize the advantages of world wide cooperation, and to minimize the disadvantages of crystallization and possible obsolescence of fundamental concepts.

Due to the initiative of CEB, a set of common unified rules for different types of construction and material is being drafted[1, 2]. Sub-committees were created within the Joint-Committee to deal with the first volume of this set of unified rules. This volume covers: objectives and general recommendations for design, design methods, basis for the determination of actions and their combinations, general conditions for use, control and acceptance of materials and components.

A brief summary of the problems discussed, of the solutions adopted and of the progress expected is presented. It is not possible to review the overall activity of the Joint-Committee. Since its creation and up to the end of 1976, the Committee had eight plenary meetings in which more than 60 contributions were presented[3]. The activity of the Editorial Group, chaired by R.E.Rowe, who drafted the main text of Volume I, and of the Sub-committees, chaired by R.Rackwitz, who drafted the Appendix dealing with Level 2 and the set of studies on First Order Reliability Concept for Design Codes[4] is particularly acknowledged.

3.2 Design Objectives

The perspective of design as a decision process is well established. The ranking of objective functions in: utility, cost and reliability, is clear. For time invariant problems general theoretical formulations conceptually correct already exist[5]

The reliability concept of achievement of acceptable probabilities that structures will not become unfit is ready to be used in much broader terms than till now. This is not the case with utility or generalized cost. These important basic concepts would need further supporting data in order to be implemented. However, the choice of the acceptable probabilities (or reliability indices) can be guided by the aim of maximizing utility or minimizing generalized cost. This leads to the consideration of cost of failure consequences and attenuation cost (increase of initial cost per unit of increase of reliability).

3.3 Limit States

The concept of limit state corresponds to a discretization of the concept of utility. Given e.g. a structural element acted on by an action-effect S of components M (bending moment) and N (axial force) there is a domain of structural behaviour within which the utility is positive, a region in which utility rapidly decreases and another domain where utility becomes strongly negative.

The region between the positive and the negative domains can be idealized as a border which limits a safe domain This border corresponds to a limit state. Often the utility surface is ondulated and several types of limit states can be defined which correspond to different borders, each one associated with a given type of behaviour (cracking, deflection, failure).

This way of thinking is satisfactory for time-invariant problems. However, this is not the general case. The negative utility associated to a limit state depends on the interval of time during which the considered behaviour (unfitness) is attained.

Limit states are usually classified into two groups: ultimate and serviceability limit states. The single occurrence of an ultimate limit state produces an abrupt reduction of utility. In serviceability limit states the reduction of utility is in general small and depends on the time interval during which the limit state is surpassed.

This duration concept is included in the unified code[1]. Actions are defined in such a way that the durations of exceedence of given values can be easily determined.

For given materials (e.g. concrete and timber) the duration of the actions affects not only the serviceability limit states but also general structural behaviour. Although the idealization of actions should allow their definition for any interval of time a standardization is advisable. At present there is the tendency to consider two durations: quasi-permanent and frequent actions[1]. The first corresponding to mean values in the probability distributions of instantaneous values (as sampled distributions) and the second to the upper 5% fractiles of these distributions. In special cases other values have to be considered[6].

The need to include in the unified code the definition of a reference time derives from the fact that probabilities due to single events (construction phase) have to be associated to probabilities of extreme values due to multiple events (variable actions). The probabilities of multiple events have to be referred to an interval of time. The interval of time of 50 years is now accepted as standard. However the theoretical formulations and the basic data easily allow to compute probabilities given any other value of the reference time.

3.4 Levels of Design

The introduction of the concept of levels of design[7] derived from the need to classify different more or less approximate computational procedures, leading to the fulfilment of design objectives.

Three design levels are considered. Level 3 is a fully probabilistic method. Design decisions are based on the expected value of the utility E(V) or on the probability of attaining a limit state, P_f.

For time-invariant problems, given a set of basic variables $\underline{X}$, the expected value of the utility is given by.

$$E(V) = \int_R V_{\underline{X}}(x)\, d\, F_{\underline{X}}(x) \tag{1}$$

where $F_{\underline{X}}(x)$ are the probability distributions of the basic variables, and $V_{\underline{X}}(x)$ measures the utility associated to them. The integral (1) is extended to the space R of all variables X.

The notions of safe and unsafe regions result from substituting the concept of limit state to the concept of utility. The probability of surpassing a given limit state, which corresponds to the probability of being outside the safe region $D_{\underline{X}}$, is given by the integral

$$P_f = 1 - \int_{D_{\underline{X}}} d\, F_{\underline{X}}(x) \tag{2}$$

All methods which allow an exact computation of the integral (1) or (2) are classified in Level 3.

Level 2 is an approximate probabilistic method.

Let the border of the safe domain $D_{\underline{X}}$ be defined by a function $g(\underline{X}, \nu) = 0$ where ν is a design parameter. One way of approximately assessing the reliability consists in measuring the distance between the mean value $\overline{\underline{X}}$ and the border

$$g(\underline{X}, \nu) = 0 \tag{3}$$

Assume that the basic variables are independent and introduce the reduced basic variables

$$y_i = \frac{X_i - \overline{X}_i}{\sigma_{X_i}} \tag{4}$$

Equation (3) becomes

$$g(\underline{y}, \nu) = 0$$

The reliability which corresponds to a given value of ν is measured by the reliability index β. The relationship between β and ν is expressed by the set of equations

$$y_i^* = \pm \alpha_i \beta \tag{5}$$

$$\alpha_i = \frac{\dfrac{\partial g}{\partial y_i}}{\sqrt{\sum_{i=1}^{n} \left(\dfrac{\partial g}{\partial y_i}\right)^2}} \tag{6}$$

$$g(y_1^*, \ldots, y_n^*, \nu) = 0 \tag{7}$$

The derivatives included in equation (6) are computed at the design point $\underline{y}^*$.

The system of equations (5) to (7) can be solved by iterative procedures.

Point $\underline{y}^*$ is a distance β from the origin, closest to it on surface $g(\underline{y}, \nu) = 0$.

Points y_i^* are fractiles weighted by parameters α_i, (8) and correspond to $X_i = \overline{X_i} \pm \alpha_i \beta \sigma_{X_i}$.

Level 1 is the so called semi-probabilistic method.

At Level 1 fixed fractiles of the basic variables are used. These fractiles (characteristic values) are multiplied by partial safety factors which do not depend directly on the limit state criterion expressed by $g(\underline{X}, \nu) = 0$.

Briefly, the algorithms used at Level 3 allow to compute accurately the values of the objective functions, at Level 2 the algorithms yield approximate values of the extremes of the design functions, at Level 1 these approximate extremes are obtained by introducing extremes of the basic variables in deterministic design functions.

In Levels 3 and 2 the basic variables are expressed by their probability distributions or at Level 2 by their two first moments. mean and variance. In Level 1 basic variables are expressed by fixed fractiles.

The classification in three design levels is arbitrary and incomplete. Levels higher than Level 3 could be introduced to express optimization criteria[9] or to include prediction decision theories[5]. Also, there are no definite borders between different levels. For instance, the partial safety factors to be used at Level 1 can be derived from computations at Level 2.

3.5 Operating Spaces

For an understanding of code alternatives for safety checking, the concept of operating spaces should be introduced[5].

The basic variables, $\underline{X}$, (actions, material properties, dimensions, etc.) define the input space.

Limit state conditions are usually expressed in action-effects, displacements, crack-widths. The space of these variables is called output space.

For some problems it is convenient to introduce auxiliary variables (e.g. strains, stresses) which define the state-space.

Direct design or safety checking can be carried out at any of these spaces. However non-linear transformations between spaces are usually necessary. For safety checking in the input space a transformation into basic variables of limit state conditions is needed, the same checking in the output space implies a transformation of the basic variable into this space. Finally, in the state-space, both basic variable and limit state conditions are to be transformed.

Usually at Level 1, utlimate limit states checking is carried out in the output space by comparing resisting and acting action-effects. This corresponds to a special format of $g(\underline{X}, \nu) \leqslant 0$ of the type $S(X_1 \ldots X_j) - R(X_{j+1} \ldots X_n) \leqslant 0$ where $S(.)$ can be identified as acting action-effects and $R(.)$ as resisting action-effects.

The mentioned formulation spaces can be used in any type of structural analysis (linear, non-linear, plastic) and of design levels. Their choice depends on operational motives.

3.6 Basic Variables

3.6.1 Actions

For many decades man has been spending much activity in the measurement of actions. However, it is only recently that these results are being interpreted under a common methodology in order to be used in design.

As indicated, the probabilistic formulation of safety implies a probabilistic definition of the actions. Consequently, available data have to be interpreted statistically in order to obtain convenient definitions.

The Joint-Committee has made a considerable effort to idealize the most important types of actions[10] Several international associations and several groups in different countries are working in the same direction.

Levels 2 and 3 can only be implemented if probabilistic idealizations of actions are given. For variable actions these idealizations should include not only instantaneous values but also extreme values for different intervals of time. Consequently, the idealizations have to be based on stochastic processes. The simplest stochastic process model which allows the combination of variable actions is of the repeated independent event type[11]. Using this simple model all the pertinent probability distributions of the parameters defining the actions can be derived from the distribution of extreme values in the reference time and from the corresponding number of repetitions[10].

Progress in the definition of actions is expected to derive not only from the use of stochastic models, more refined than this one, but particularly from improved prediction decision rules, allowing to build pragmatically optimal models[5], and also from the consideration that several types of actions are man-produced or man controlled.

3.6.2 Mechanical Properties

The relationship between control and definition of mechanical properties should be very intimate. Efforts along these lines yielded an improved definition of types of control and acceptance rules[12]. Progress depends not only on better theoretical approaches which allow to incorporate all information available in the probabilistic definition of mechanical properties, but also on improved cooperation with the industries of materials of construction to compatibilize the needs and interests of the owners, the designers, the builders and the producers of materials. Mutual information and national and international actions are required.

3.6.3 Dimensions

Dimensional tolerances are often viewed as a constructional and not as a structural problem. For structural purposes dimensions are usually taken as deterministic quantities. When the probabilistic variability has to be considered, the present tendency consists in extending to structural problems the concept of tolerances and assigning upper and lower limits of the dimensions to be introduced in structural design expressions.

In future, dimensions should be dealt with as other basic variables by defining their probability distributions and by fixing control and acceptance rules to fulfil both constructional and structural objectives.

3.7 Combination of Actions

Given a variable X of probability distribution $F(X)$, the probability distribution of the extreme values obtained by r independent repetitions of X is expressed by

$$F_r(X) = (F(X))^r \tag{8}$$

This simple expression allows to transform distributions of instantaneous values into extreme distributions for any value of r (the r repetitions being assumed to correspond to non-correlated trials).

If n different types of actions act simultaneously, design should be checked for n combinations of actions each one corresponding to the case in which one of the actions assumes its extreme value in the reference time. The computation procedure is the following:

The n actions are ordered according to their number of repetitions, $r_i \leq r_{i+1}$.

The probability distributions to be used in each combination are obtained assuming the number of repetitions indicated in Table I[7].

TABLE I

Number of Repetitions to be Considered in Each Combination

Combination Number	*Action number and number of repetitions in the reference time*				
	1	2	3	...	n
1	r_1	r_2/r_1	r_3/r_2	...	r_n/r_{n-1}
2	1	r_2	r_3/r_2	...	r_n/r_{n-1}
3	1	1	r_3	...	r_n/r_{n-1}
⋮	⋮	⋮	⋮		⋮
n	1	1	1	...	r_n

When used at Level 1 this combination rule corresponds to reducing the characteristic values of the actions. In the Unified Code this reduction is introduced through a combination factor, ψ_0. In the same way, coefficients ψ_1 and ψ_2 are introduced to transform extreme characteristic actions in the reference time into actions with different durations. The combination rules which include actions of different durations are also included in the Unified Code.

3.8 Structural Behaviour

In the optics of safety checking the study of structural behaviour consists in the transformation of variables between operating spaces. In general the transformations are non-linear.

The simultaneous transformation of all variables from the input to the output space or reciprocally is in most cases difficult to handle. For this reason it is convenient to split the problems into (i) transformations which allow to determine the limit state surface (resisting action-effects) in the action-effects space (members analysis) and (ii) transformations which allow to obtain the action-effects acting on the members as a function of the combined actions (structural analysis)

This corresponds to a formulation of the type $S \cdot R$, in the generalized sense of considering the multi-dimensional character of S and R and consequently defining the space variability of S and the safe domain of action effects limited by R. In this formulation the border of the safe domain is no longer deterministic but random. It can be determined using the weighted fractiles method.

The probabilistic variability of the acting action-effects has to be derived from the variability of the actions taking in due consideration the non-linearity of the transformation $S(X)$. Also, in this case a linearization procedure should be adopted.

At Level 2 it would be convenient to implement algorithms which would allow the combination of the two problems and consequently a unified linearization and definition of weighted fractiles.

In future, dimensions should be dealt with as other basic variables by defining their probability distributions and by fixing control and acceptance rules to fulfil both constructional and structural objectives.

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⋮	⋮	⋮	⋮		⋮
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The concept of the factors of structural safety presently applied to the design of fixed-wing aircraft can be traced back some 50 years. The last decades have brought about rapid progress in establishing aerodynamic derivatives, defining load conditions and predicting structural loads as well as enabling more detailed analyses for stress and deformation to be made. The lack of a rational basis for the factors of safety together with the progress made brought about a discussion of changing the concept and the factors involved.

The three pilot papers contained in this report address the different aspects which are envisaged, and show up inconsistencies of the present concept as well as means and methods for possible changes and examples of the outcome. An additional paper summarizes what is going on in the field of civil engineering with respect to structural safety.

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